THE SEASTEADING INSTITUTE

Seasteading Engineering Report
Part 1: Assumptions & Methodology

Eelco Hoogendoorn
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Our Mission: To further the establishment and growth of permanent, autonomous ocean communities, enabling innovation with new political and social systems.

Email: eng@seasteading.org website: www.seasteading.org

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PART 1: ASSUMPTIONS & METHODOLOGY

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Author: Eelco Hoogendoorn

Acknowledgement: Miguel Lamas Pardo, Bart Kemper, Alexia Aubault, Michael Santos

NOTE: Please send any feedback you might have regarding content to eng@seasteading.org.

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2 Preface

This document is a high-level analysis of the engineering challenges involved in homesteading the high seas. The aim is not to provide a detailed design of a specific seastead, but rather to find answers to general questions, such as the cost per unit area of functional real estate.

There are many different ways to enable living on the oceans, from oil platforms to cruise ships, to untried concepts. The goal of this document is to facilitate the identification of a promising candidate concept that best meets TSI's criteria. In a way, living on the water is a solved problem: houseboats offer floating real estate at a cost indistinguishable from that on land, and cruise ships provide luxurious accommodations on the open ocean. However, the former do not function outside of protected waters, and the latter are expensive. Considerations of cost are of paramount importance, and the problem can be stated as identifying an optimum of the relation between cost and functionality.

The main types of ocean going structures can be classified as ships, semi-submersibles and spar platforms. This classification is not perfect: some concepts are best regarded as falling somewhere in between these archetypes. Some concepts fall outside this classification, and will be treated separately.

The problem of selecting a good strategy involves a wide spectrum of considerations, including political, oceanographic and personal preference. Many parameters still contain significant uncertainty, and definite conclusions cannot be reached on all fronts. Regardless, the goal is to uncover as much relevant information as is possible. To this end, a wide variety of designs will be evaluated with regard to the key criteria, in the context of a set of likely scenarios.

This paper is split in two parts; a section where the assumptions made and methodology used are described, and a section where specific designs will be analyzed using this framework.

3 General

3.1 Innovation

Existing structures that enable living on the ocean are not built with the explicit purpose of living on the ocean as a goal in itself, with the exception of the ship known as (The world of) Residensea. Most living on the ocean that happens today is a means to the ends of transportation or resource extraction.

Given the fact that Seasteading presents a specific and novel set of goals, the approach of taking existing conceptual designs and retrofitting them for Seasteading may be missing out on opportunities for achieving a more effective design.

This observation should be balanced against the fact that innovation is expensive, and the resources of TSI are limited. Only if a concept is identified that promises to significantly outperform either an adapted ship or adapted platform should such an innovative strategy be pursued. Additionally, candidates serving different goals may be identified, such as a solution for the long term and a solution for the short term.

3.2 Scale

The overall scale of a seastead concept influences many aspects of Seasteading; among which are financial, engineering and societal aspects.

- **Financial**: The most direct aspect in which scale manifests itself is financial. All proven concepts for living out on the ocean, from oil platforms to cruise ships, are large-scale structures. This manifests itself in price tags of a hundred million dollars and upwards. This kind of money clashes quite strongly with the notion of small incremental steps.

  Ideally, a seastead would be able to scale down all the way to the size of a single autonomous house. Although this seems unlikely to be accomplished, this is not an all or nothing situation, and trying to approach this ideal as close as possible is worthwhile.

- **Engineering**: Big structures with a reasonable price per unit floor area are known to exist, but a smaller version of such a concept would be preferable. However, typically, the size of a concept is a feature of its design. Scaling down a cruise ship yields a small ship. Small ships are only comfortable in calm seas. Scaling down a spar that extends far into the water undisturbed by waves yields a structure that has the bulk of its presence right in the middle of the wave action.

  In general, smaller structures are more responsive to wave motion, and big structures are more expensive, both of which are undesirable. The goal is to find a design that best unifies these conflicting demands.

- **Societal**: Dynamic geography (DG) rests on the premise of being able to move real estate around with little effort. If a house/apartment is locked into a big vessel with many other apartments, its physical location relative to its direct neighbors is fixed. This still allows for dynamic geography on the scale of the vessel itself, but ideally, DG would be enabled on as fine-grained a scale as possible.

  Aside from the increased difficulty of funding a large structure, it has societal implications as well. Who will finance the investment, and what will the position of the investor be within this community? This is perfectly compatible with some models of anarchocapitalism, but essentially rules out bottom-up grassroots community building.

In conclusion, there are compelling reasons to aim for a small-scale incremental seastead design; it is more likely to get off the ground, and it enables more socio-political options. On the other hand, it increases the engineering difficulty.

3.3 Materials

As a construction material for the hull, essentially two candidates exist: concrete and steel. These are the materials with a cost per unit strength ratio unrivaled by any other options on the market today. For instance, contrary to popular belief, plastic is not cheap; it is merely cheap to process where small parts are concerned. Its cost per unit strength is especially unattractive. Aluminum and composites are both a priori unlikely candidates for the same reason: they deliver weight savings at a high cost. Weigh is not a pressing criterion for a seastead--cost is.

The prevailing construction material in the offshore industry is steel. Concrete is used for some offshore platforms, primarily ones placed on the ocean floor. Some concrete ships have been built in the past, but the practice has not caught on.

The fact that concrete is not in favor with the shipbuilding industry today does not mean it will not be the most appropriate material for seasteading. The additional displacement and associated fuel costs have been found to be prohibitive for shipping in the past. The fuel cost and loss of mobility relative to a steel hull may well be outweighed by the advantages offered by concrete, given that shipping and seasteading have very different priorities. This is reflected in the fact that concrete is on the rise for offshore oil storage and production barges; it has been found to outperform steel for these mostly stationary structures as well.

3.3.1 Steel

Steel requires maintenance for two reasons: corrosion and fatigue. Neither of these problems is completely preventable, necessitating periodic maintenance checkups.

It should be noted that nearly all marine structures in existence today are either ships, undergoing regular dry-docking, or oil and gas platforms, both being designed for short (20-25 year) service lives.[1] Ships are scheduled for extensive dry-docking at least every five years; this is partially driven by bio-fouling/mobility considerations that would not be significant for a seastead. The optimal interval for a seastead may be longer, but would still be subject to inspection for corrosion.

Maintaining offshore steel beyond 25 years without dry-docking is possible, but this requires extensive on-site operations, for which no cost indications have been found. However, it is likely to be expensive; betting economical onsite maintenance seems imprudent. This has implications for designs which either have too much draft or too limited mobility for dry-docking. These structures will have to amortize their capital costs over a relatively very short time (a 20-25 year service life being 'short' for a seastead) which may reduce their financial viability.

3.3.2 Reinforced Concrete

Reinforced concrete has fewer maintenance issues than steel, if properly constructed. However, if loaded in tension, concrete will develop cracks over time, which may cause the steel reinforcing bar (rebar) to corrode, resulting in a potentially unacceptable decrease of an already low tensile strength.

Given the lower yield strength of concrete compared to steel, supporting a given load requires far more concrete than steel, in terms of volume. Even though concrete has a lower density, this translates into heavier components, by about a factor 2-3 for standard concrete. The estimated cost per unit strength of concrete appears to be somewhat lower as compared to steel, but not drastically so. However, the near absence of maintenance costs for properly constructed concrete is the strongest argument in its favor.

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[1] http://www.stoprust.com/7cpforfpsos.htm

3.3.3 Tensioned Concrete

Tensioned concrete, even though it resembles reinforced concrete in consisting of a composite of concrete and steel, has rather different applicability. It consists of reinforced concrete with tensioned steel tendons. This results in a material with much improved strength in tension. In tensioned concrete, the tensioning tendons are effectively carrying all the loads, and the concrete fills the role mainly of corrosion protection and a non-thermal bond between the steel. Due to the fact that the tendons need not be welded, but are embedded in the concrete, much higher strength steel can be employed: the yield strengths of these tendons are higher by a factor 8 compared to typical grades of steel. It is believed that the majority of existing concrete barges are built using tensioned concrete.

Cylindrical vessels which are loaded by a dominant compression force, such as spars and submarines, could be constructed out of reinforced concrete; elongated structures such as ships/barges, that may experience large net tension forces, can only be effectively realized out of tensioned concrete.

The novelty introduced by the use of concrete is minor; projects of various kinds have been realized in concrete before, and they have had neither technical problems, nor problems obtaining approval by a classification society or securing insurance. Nonetheless, working in concrete will be far less convenient than working in steel: there is no continuous fluid offshore concrete industry like there is for steel. The need for large temporary docks and a large temporary workforce complicate comparisons with steel construction[2] .

3.4 Some numerical properties

3.4.1 Steel

- Cost: $5,000US per ton of yard cost for simple/routine project.[3] Estimates up to $12,000US per ton have been found[4]; the latter seems more congruent with the costs of recently delivered semi-subs.
- Yield strength:
  - 200MPa (typical shipyard steel)
  - 320MPa (high yield shipyard steel)
- Density: 7800kg/m3

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[2] Offshore Structures – A new challenge: How can the experience from the marine concrete industry be utilized: http://www.tekna.no/arkiv/NB/Norwegian%20Concrete/Offshore%20Structures.pdf

[3] http://seasteading.org/mission/additionalreading/clubstead

[4] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

- High maintenance costs due to corrosion and fatigue. Typical guaranteed lifespan of non-docking offshore structure is 25 years.

3.4.2 Reinforced Concrete

- Cost (material + rebar + labor):
    - Gravity Dams built in North America: $200-400US per m3. Large volume, simple geometry: Low end estimate.[5]
    - Float, Inc: $361US per cubic-yard 1999, $612US/m3 2009 (claimed, not demonstrated). [6]
    - Concrete subs: $330US per ton displacement, or ~$1,000US/m3 demonstrated. Low labor cost, but high complexity geometry. [7]
    - Post tensioned on-site concrete bridge construction: $1,700US/m3[8]
    - Summarizing: no clearly interpretable figures for actual offshore concrete have been found, but $1,000-1,500US per cubic meter seems like a reasonable estimate for large-scale in-dock construction. At a nominal density, this corresponds to about $2,000-4,000US per metric ton.
- Yield strength (compression)
    - 20-25MPa typical
    - 50-80MPa high grade [9]
- Density: 2700kg/m3 typical. Alternatively: 1900kg/m3 @70MPa described in (Nawy, 2008) [10]. May be a good candidate for concrete spar.
- No maintenance with passive monitoring of tendon quality, and very long life if rebar is properly protected (up to 200 years claimed).

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[5] http://www.cement.org/water/dams_rs_cost.asp

[6] http://www.floatinc.com

[7] http://concretesubmarine.com/

[8] http://www.dot.state.fl.us/Structures/StructuresManual/CurrentRelease/DesignGuidelines/SDG9.1General.htm

[9] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

[10] http://books.google.com/books?id=1OwkUrXuhjQC&pg=PT549&lpg=PT549&dq=Elf+Congo’s+

3.4.3 Tensioning tendons

Yield strength: 1800MPa[11]

Cost of tendons is not dominant relative to the other materials and labor employed in the construction of tension concrete. The increased cost of tensioned concrete is mainly in the labor costs. [12]

3.5 Concepts

The main goal of the present engineering research is the identification of a concept that best meets the needs of seasteading. The many particulars of such a concept are secondary; the primary concern is the selection of a hull type. To this end, the following hull types will be considered; they and their terminology are briefly introduced below.

3.5.1 Displacement hull

The displacement hull is a broad category, consisting of everything from ships to floating islands to barges, or anything in between. The various types of displacement hulls considered in this report are briefly described below.

Ship: The most common type of displacement hull comes in the form of a ship, which has an elongated shape. This slender shape minimizes drag to maximize mobility.

Barge: A barge can be defined in different ways in different context, but the essence of it is a simplified ship. A barge typically has a simplified geometry, emphasizing useful internal volume or deck space at the expense of drag; whereas ships are self-propelled, barges typically are not.

Island: All displacement hulls without a ship-like or barge-like shape can be considered floating islands. Several such concepts have been proposed in the context of permanent living on the ocean. Compared to ships or barges, a floating island has many drawbacks, primarily related to mobility and station keeping. In large enough scale, a floating island may offer greater comfort in waves and more versatility in arrangement, but also presents unique challenges in construction and deployment.

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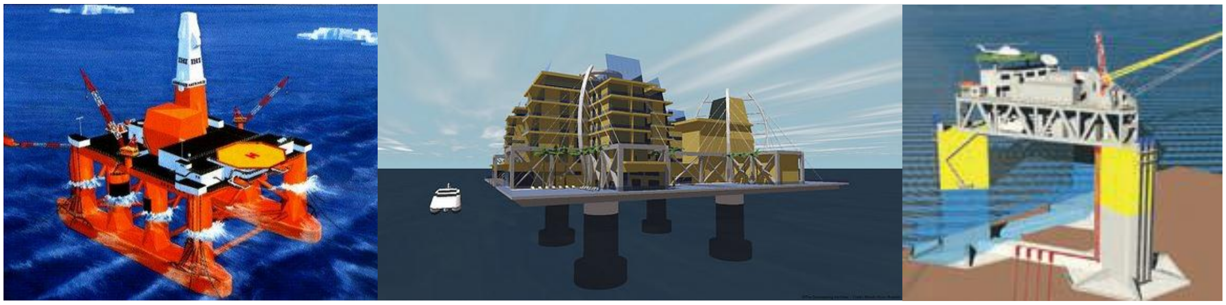
[11] http://www.abam.com/uploadedfiles/tp-World'sLargestPrestressedLPGVessel.pdf

[12] http://www.dot.state.fl.us/Structures/StructuresManual/CurrentRelease/DesignGuidelines/SDG9.1General.htm

VLFS: Some concepts have been proposed under the acronym VLFS, or Very Large Floating Structures. They are typically large displacement hulls, differing from ships or barges mainly in scale and associated practical considerations. However, while the literature on VLFS offers some useful information, initial seasteads are likely to be much smaller in scale, so consideration of these structures is relevant mainly in the longer term.

3.5.2 Semi-submersible

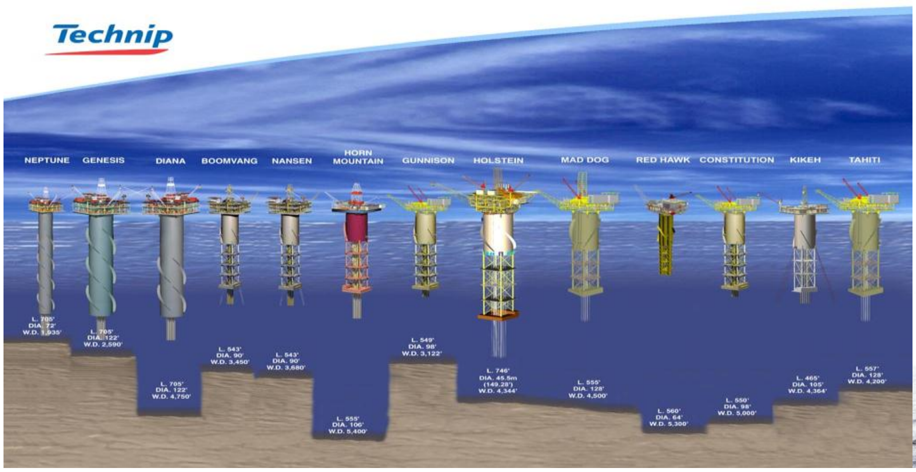
A semi-submersible (semi-sub) is characterized by submerged pontoons, connected to a raised topside by several columns. The fundamental principle in semi-submersible design is to de-couple waterplane area and waterplane inertia, thereby achieving adequate static stability and superior dynamic response in waves. By minimizing waterplane area, the natural periods of pitch, roll, and heave motion can be increased to avoid resonant excitation in waves; but by spreading the columns, the moment of inertia of the waterplane area is increased, to provide the necessary static stability.



- **Typical**: semi-subs are a concept developed in the oil & gas industry. They come in a large variety of sizes and costs, starting around $200M.
- **ClubStead**: ClubStead is purposely-designed seastead by MI&T, based on a hull of semi-submersible type. Detailed documentation can be found on TSI’s website.
- **MiniFloat**: an adaptation of the semi-sub paradigm, also designed by MI&T. Using large heave-plates, it aims to enable the creation of smaller semi-subs.

3.5.3 Spar

Spars are characterized by a vertically elongated hull supporting a raised topside module. This design allows for minimal coupling to wave-motion



- **Typical**: Spars are mostly used in the oil & gas industry. The spars employed here are large constructions, with depths over 250m. These structures are hard to build, with a matching price tag; they are in many ways over-engineered for seasteading purposes, and are therefore not a likely optimal candidate.

- **FLIP**: FLIP is an oceanographic research vessel, the first spar ever to be built. It is much smaller than the typical oil & gas spar, having a draft of roughly 90m. Spars similar to FLIP may be attractive candidates in the right location, but the geometry inherently offers minimal useable deck area in proportion to the hull's principal dimensions.

3.5.4 Submersible

Submersibles are seasteads located entirely below the waterline during normal operation. Unlike what is suggested by military submarines, this could actually be one of the cheapest options. Their most compelling feature is the absence of tension between scale and comfort; but the obvious drawback is the absence of sunlight, fresh air and open space. If a submersible is configured to have its accommodation spaces above the surface of the water, then in many respects it becomes a semi-submersible!

3.5.5 Other

Various other, more unorthodox designs will be considered as well, such as platforms based on indirect displacement, and articulated systems, such as the VersaBuoy.

4 Oceanography

There are still many unknowns to the input of any engineering design, both political and environmental in nature. These options are simplified into several location scenarios, consisting of a set of assumptions and their consequences. The key properties considered here are distance to land, which is very important both in terms of political climate and bootstrapping a community/economy, the possible methods of station keeping, and the most significant environmental variable; worst case wave conditions.

4.1 Locations

4.1.1 International waters

The best option in terms of political independence is residing in international waters. International waters are found 200+ nautical miles away from coastal states.

- **Location**: 200+ miles from land. The 200nm limit does not apply to all locations; if the continental shelf extends beyond 200nm and the same legal claims are extended, the limit may then be as much as 350nm from land. However, it is presumed that suitable locations are available where the continental shelf does not extend beyond the EEZ.

- **Water depth**: Due to the legal definition of the continental shelf, international shallow waters are rare, and thus unlikely to coincide with other criteria for a good location. In this scenario, it is assumed they are not available.

  NOTE: The EEZ was originally defined as all waters within 200nm from land. The area known as the continental shelf carries the same claims regarding economic activity and permanent installations. Since the continental shelf is effectively defined as 'all shallow waters adjacent to the EEZ' (the definition is very complex, but this is what it boils down to for seasteading purposes), it seems as if politically free shallow waters are rare. Note that there is a difference between the geological definition of the continental shelf, which includes a 100-200m water depth definition[13] and the legal definition [14]: The latter is more expansive, and allows claims up to 2500m of depth.

- **Wave**s: Waves may get big; 200nm fetch is enough to produce large waves, so even the landward side need not be safe. The metocean data from the ClubStead report describes a 100 year storm with H_s=8.3m off the coast of southern California. (H_s stands for significant wave height, which is described in detail in the Waves section.) Further searches suggest that these are indeed relatively calm conditions, as far as international waters are concerned; more benign locations have so far not been identified. (Rough estimates from the east coast of South America suggest these waters might offer some improvement over ClubStead conditions). ClubStead conditions are measured a hundred miles off the coast of San Diego; because there are no geographic features suggesting otherwise, they are presumed to be comparable 200 miles off the coast.

- **Station keeping**: For the water depths prevalent beyond the EEZ, mooring may not be an option; not only are the economics questionable, but the deep water results in an anchoring/modularity conflict which strongly favors dynamic positioning [see the section on mooring for elaboration].

The distance from land is a significant obstacle in this scenario. Travel to land will take around ten hours by ship. This presents a barrier to entry for seasteading, as presumably few people would be willing to

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[13] http://en.wikipedia.org/wiki/Continental_shelf#Geographical_distribution

[14] http://www.un.org/Depts/los/clcs_new/continental_shelf_description.htm

live in a small community if it were isolated to this degree. This raises the question whether this is an appropriate first step, or whether a seasteading community of sufficient critical mass should be bootstrapped, starting closer to land.

4.1.2 Seamount

The oceans harbor many seamounts that do not pierce the surface and are outside, yet relatively near, an EEZ. This would provide mooring opportunities in international waters.

- **Location**: 200+ miles from land.
- **Water depth**: between 50-150m is typical for many seamounts.
- **Waves**: no improvement over deep waters can be assumed. These shallow waters are typically not shallow enough to provide any noticeable wave attenuation. Since such locations will have by definition at least 200nm fetch on all sides, significant waves cannot be ruled out from any side, in general.
- **Station keeping**: mooring in these water depths is quite feasible, and maintaining platforms in close relative proximity should not be an issue. However, for hull forms with a directional axis, such as ships and barges, any mooring system that restrains the orientation of the hull may be highly undesirable because (if it is assumed that waves can come from any direction) taking seas on the beam can lead to potentially large rolling motions. Systems such as a single-point mooring or a turret mooring allow the hull to 'point' into the prevailing seas, but the former requires a much bigger watch circle, and the latter is a very expensive solution. Of course, ships or barges could use dynamic positioning, but then the seamount would not really offer advantage over the open ocean, but rather it would simply impose another constraint on location. Hull forms that have no 'preferred' orientation (such as semi-subs or spars) are more viable candidates; however spars are typically designed to have a draft of 150m or more, so (alas!) may not be suitable for a 'shallow' seamount location.

Many locations satisfying these criteria have been found, Ampere seamount being one with particularly favorable characteristics. It is just outside the EEZ of Spain and Morocco on an existing ferry route; the water is very shallow and hosts a plentiful variety of marine life.

However, it directly faces the Atlantic Ocean. Detailed wave data are not yet known at the time of writing, but snapshots from recent wave activity suggest it is likely this area has larger waves than the ClubStead scenario.

In general; potential locations are already highly constrained by the demand for moderate waves in combination with a good socio-economic climate. Even though there are many seamounts, they cover only a fraction of the total water surface; adding this constraint is likely to force one to compromise on other important conditions. However, the seamount scenario offers a number of potential advantages; certain issues with respect to mooring and maintaining relative proximity between platforms remain to be addressed, but these issues are much more easily resolved in the shallow waters of a seamount than in the deeper waters of the open ocean.

4.1.3 EEZ

The basic premise behind this scenario is that residing in a host nation's EEZ is acceptable, perhaps due to a favorable legal interpretation, a contract with a host nation, or (temporary) concessions from the seastead community. If a seastead is a positive influence on its surroundings, and it is sufficiently mobile, jurisdictional arbitrage can be leveraged.

- **Location**: 12 (24)+ nm away from shore
- **Depth**: Water depths of any choice assumed to be available
- Waves can still become large in most parts of the EEZ, but by appropriate choice of location, on the leeward side of the prevailing winds of land masses for instance, locations outside territorial waters can be found having a significant wave height not exceeding H_s=3-4m. Ideally, a location with highly uniform wave directionality is found, such as for instance the Gulf of Finland.
- **Station keeping**: Mooring is both affordable and does not suffer from modularity conflicts; units can be moored close together. Dynamic positioning may still be preferable in locations with low external forces.

This scenario both increases and decreases the need for mobility. Due to the possibility of mooring without any complications, mobility requirements are less of a concern with respect to currents; locations with significant currents would be feasible in terms of operating costs. On the other hand, due to residing in claimed waters, having the option to move over long distances if the political climate turns around is a necessity (alternatively, this scenario may be regarded as an intermediate stepping stone, where it is taken as a given that political independence will be limited in this stage).

The following sections discuss several potential EEZ locations; it is not implied that a comprehensive search of these regions has been performed.

4.1.3.1 Mediterranean

International waters do not exist in the Mediterranean, as there are no points further than 200nm from land. In general, worst-case wave conditions in the Mediterranean are not necessarily an improvement over ClubStead conditions; a maximum H_s=8-9m can be found in many places.

Favorable exceptions are found on the leeward side of land masses. An example of such a location might be off the east coast of Malta [15], where a maximum H_s=3-4m is found. However, this location is arguably lacking in proximity to a population hub and economic activity. The Hadrianic sea has more nearby cities, and waves up to only H_s=5.5m[16] under rare circumstances.

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[15] http://www.capemalta.net/maria/pages/level1/

[16] http://www.map.meteoswiss.ch/map-doc/icam2005/pdf/poster-sesion-b/B08.pdf

4.1.3.2 Baltic Sea

For the Baltic as a whole, the worst-case scenario[17] of H_s=7m is again not a large improvement over the ClubStead 100-year storm.

The Gulf of Finland, offers a combination of moderate waves (max H_s=5.5m)[18], nearby cities and a warm political climate. However, the actual climate is less ideal; the northern half of the Baltic can get covered by ice up to half a meter thick.[19] If this ice is moving in any way, as it eventually will, it may produce an unmanageable complication for any moored structure. A vessel with dynamic positioning could easily relocate if icing conditions became untenable, although this would constitute a significant upheaval in the course of operations.

The eastern coast of Denmark offers some locations that are outside of territorial waters, yet highly geographically sheltered and shallow. These scenarios are described in greater detail in the upcoming location research document.

4.1.3.3 South China Sea

Conditions as found in the South China Sea [20] are fairly benign, with a hundred year storm of H_s=6.5m, with insignificant swell. Little else is known about the desirability of this location, and the political climate is questionable, but it stands to reason these island regions offer many relatively sheltered locations. Typhoons (tropical storms) are a significant complicating factor that would have to be taken into account.

4.1.4 Free-floating

Another scenario is the free-floating scenario, where a seastead is neither anchored, nor makes a (significant) effort to influence its course. Arbitrarily drifting over the entire globe is not deemed an acceptable strategy. Instead, the idea is to find a geographic location having little or no time averaged drifting forces.

- **Location**: variable, but far from land most of the time if stable gyres are to be utilized.
- **Depth**: generally deep; but if a spar-like concept is chosen, this may restrict access to coastal waters
- **Waves**: the worst storms are typically clustered in a single season. If these conditions can be avoided, this could potentially lead to much reduced worst case wave heights, regardless of operating in the open ocean.

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[17] http://www.coastalwiki.org/coastalwiki/Using_satellite_data_for_global_wave_forecasts

[18] http://www.fimr.fi/en/tietoa/veden_liikkeet/en_GB/aaltoennatyksia/

[19] http://www.fimr.fi/en/tietoa/jaa/jaatalvi/en_GB/2003/_print/

[20] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

- **Station keeping**: position keeping is only required relative to other seasteads, rather than relative to a fixed global position. For seasteads of similar drag characteristics, the effort required to achieve this goal tends (theoretically) to zero.

However, any such gyre scenario will nearly invariably take one far from shore most of the time, which clashes with the desire to operate as close as possible to population centers, to minimize the costs imposed by isolation.

One interesting scenario proposed by Vince Cate is following the Gyre in the Sargasso Sea. His research suggests that the period of going once around this gyre is nearly one year, so with only minimal external forces, a yearly migratory pattern could be established. This migration could be chosen such as to avoid both northern winter storms, and the southern hurricane season. A detailed analysis of the minimum worst case H_s thus attainable has not been performed, but it seems plausible a substantial improvement could be achieved.

4.1.5 Territorial waters

- **Location**: all the way up to shore

- **Depth**: potentially severely constrained. For instance, the SF bay might not even offer 20m, excluding shipping lanes. This would rule out concepts with high draft, such as spars.

- **Station keeping**: easy mooring, especially in areas with no significant currents.

- **Waves**: significantly easier compared to locations offshore, especially if the seastead is within an area such as a bay that offers protection from the sea.

Inside territorial waters, no amount of political autonomy is expected. In many places, even temporarily residing there will be heavily regulated, even without any political aspirations. Therefore, a design that merely works in these conditions is not a valid candidate. However, if a design does work in these conditions, it is a definite plus, as it would facilitate bootstrapping, and enable pulling into a port, might the need arise. For instance, most ships would work inside a bay, whereas a spar would be too deep for any bay or harbor that has been investigated.

4.2 Recommended oceanography

This section lists some questions in oceanography that are deemed to have priority as far as their relevance to future engineering decisions is concerned.

- **EEZ wave/metocean data**: Operation inside the EEZ may be politically feasible. Yet we have thus far found few EEZ locations that are less severe than that considered in the ClubStead design, as a benchmark. Some locations with maximum H_s=3-4 meters have been identified, but they are not the norm. Can we find locations combining consistent low waves and other desirable criteria? Several such locations in relative proximity (for instance, within the Mediterranean) would be ideal, as it would allow for jurisdictional arbitrage.

- **Current strength**: some concepts, most notably spars, are very sensitive to current strength. Identifying locations with a minimum average current, and obtaining an impression of what can reasonably be expected as the extreme current would be highly useful. Having a time-series for each candidate location would be most informative. The 1-knot scenario wielded now may be unnecessarily conservative. If this could be lowered by a factor of two, required fuel consumption would drop by nearly an order of magnitude (there is a limit to this substantial rate of decrease however; as the current becomes smaller, other forces start to dominate)

- **Gyre scenario**: the free floating gyre scenario has not made it into this version of the document, but if a more detailed study shows significantly improved worst case storm conditions, the disadvantages of residing far from any economic activity most of the time may well be outweighed by the simplification of the engineering problem and associated costs.

- **Wave directionality**: elongated shapes such as ships and barges are sensitive in their operation to the amount of spread in the wave directionality. Especially cross-seas, with waves generated in two different wind systems, are noted as a hazard to ships. Such sea-states are likely to interfere with concepts that depend on their orientation towards the waves for operation. For instance, ClubStead metocean indicates a 100-degree angle between the predominant swell and wind directions. Information on the magnitude of wave and swell components individually would be useful; perhaps one of the components is significantly smaller. Closer to land, such as in the Gulf of Finland, uni-directionality is expected. Due to proximity to land, it is expected many EEZ waters will display this characteristic, but identification of international waters having rather consistently unidirectional seas at least most of the time, would be very desirable as well.

5 Mobility

5.1 Introduction

This chapter explores various facets of mobility as related to a seastead. Mobility is to be interpreted broadly; the analysis of moving or station keeping by engine, or station keeping by anchor.

5.1.1 Political importance

Mobility has an important political aspect. Even though the sovereign powers of a nation technically do not extend beyond their territorial waters, permanent installations in the EEZ are regulated with regard to most aspects. All vessels have right of free passage. What exactly distinguishes free passage and permanent installations is unclear, but a permanently anchored structure probably does not qualify as passage. Whether a non-anchored loitering vessel would qualify is not clear.

If loitering would provide freedom from EEZ restrictions, this would be a very strong argument in favor of using dynamic positioning in preference to mooring. In fact, the political importance could very well lead to a decision to use dynamic positioning rather than mooring, irrespective of relative cost or other engineering considerations.

5.1.2 Engineering importance

When designing a stationary platform for a given location, the problem is not coping with the everyday conditions, but with the extreme states. This is unfortunate, since there is no such thing as a guaranteed maximum wave height. The design will have to be dimensioned to accommodate the 'long tail' of the probability distribution governing the occurrence of worst case events.

On the other hand, a seastead with sufficient mobility is potentially capable of seeking shelter in advance of extreme storm conditions that may be predicted. How much mobility is required depends on many factors, such as the extent and speed of the storm, the proximity of sheltered locations, and the reliability of weather forecasting in the region. However, there is a clear division between seasteads capable of having this ability and those unable; only ship-shaped seasteads are likely to attain the required mobility.

5.2 Degrees of mobility

We can distinguish several degrees of mobility:

- **Fully migratory**: a seastead mobile enough to be able to continuously move at considerable (several knot) speeds, without incurring a prohibitive cost. It is not obvious that any concept meets this criterion: even for ships, the associated costs will be substantial.
- **Occasionally migratory**: moving over long distances would be affordable once in a while, but not on a permanent basis. This is certainly affordable to ship-type constructions; perhaps marginally affordable for barges, and less so for semi-subs. Not likely to be feasible for spars.
- **Station keeping**: a seastead that is capable of maintaining a fixed position in spite of environmental forces.
- **Lazy station keeping**: a seastead that is capable of maintaining its position in a time averaged sense. Large storms may push it away from its neutral position, but it will be capable of maintaining a constant political/natural climate.
- **Free floating**: no propulsion at all. This approach is not considered in the present paper due to its limitations, and the legal/practical uncertainties associated with this mode of operation.

Concepts are required to at the very least be capable of lazy station keeping. But beyond this, it is not immediately obvious what degree of mobility is desirable. Seasteads capable of merely lazy station keeping would require a thorough answer to the question of how to avoid collisions between them, as the external forces need not be perfectly uniform among seasteads.

Relative to a ship, mobility is an obvious factor to economize on, since moving around is not the core purpose of a seastead community. However, designing for a high level of mobility does offer advantages, even if the possibility is not used often, for the political and engineering reasons mentioned above.

5.3 Dynamic geography (DG)

All dynamic geography requires a degree of mobility. We can distinguish two classes of dynamic geography.

- **Internal DG**: repositioning relative to other Seasteads. This merely requires the ability to move small distances at low velocities. All seastead concepts, with the exception of those whose functioning depends on contact with solid ground (towers, tension leg platforms, which are therefore not considered at all by TSI) will be capable of this type of movement. Internal DG can occur at a variety of scales, depending on the particular seastead type; a large seastead can in principle only move as a single whole. However, if a modular form of construction is employed upon the seastead hull (for instance, based on shipping containers), DG will be possible up to the individual scale.

- **External DG**: repositioning relative to other nations / environmental condition. If the political attitude of the nation whose sphere of influence a seastead resides in becomes hostile, the ability to move over long distances would be desirable. The economics of such an operation are non-trivial; not all concepts are expected to be able to meet this criterion economically.

5.4 Station keeping

As noted above, all seastead concepts should at least be capable of lazy station keeping. While one of the attractive features of floating real estate is that moving it is far cheaper than moving real estate on land, the flipside is that most of the time, one does not want real estate to move, yet if kept unchecked on the ocean, it will.

Station keeping can be accomplished in essentially two ways: Mooring or dynamic positioning.

5.4.1 Mooring

In this context, mooring refers to a professionally deployed (semi)permanent system of anchors; this is a much more involved process than the simple anchor-chain-windlass anchoring systems commonly found on seagoing vessels. Conventional anchoring systems cannot be relied upon to hold vessels in close proximity during extreme storms, and would pose a substantial risk of collision damage.

5.4.1.1 Deep water mooring

The only useful cost data concerning deep-water mooring that has been identified in the course of the research is in the MiniFloat technical documentation. Material costs for mooring a 1600st structure are estimated at 1M$, and at 4M$ for a 5500st structure [4]. This amounts to roughly 1/4th of the estimated cost for hull construction, exclusive of any topside facilities or equipment. This is for a large water depth of approximately 2000m.

Mooring a vessel in deep water requires catenary mooring lines. The footprint of these spread catenary mooring lines has a radius of about twice the water depth. This implies that a dense formation of seasteads cannot be formed by means of mooring, as crossing mooring lines do not seem feasible given the way they are installed (dropping and/or dragging the anchor with the cable pre-attached). With some care, seasteads could be moored into a line-formation without running into problems with crossing mooring lines though, but if such lines are to be spaced miles apart, this is still of questionable density.

Since mooring lines need to have some slack in them, a moored vessel can move around its neutral position, it’s so called watch circle. *“The typical, watch circle is 80-200m when FLIP is tri-moored in 4 km* *water".* [source: FLIP documentation]. Considerations hereof also limit the usefulness of deepwater mooring for multiple seastead platforms, if collisions between seasteads are to be avoided.

5.4.1.2 Shallow water mooring

The cost and complexities of mooring are very much a function of depth. When shallow waters are available (up to 200m), mooring is certainly the cheapest option, although this cost advantage will have to be weighed against the advantages offered by a higher degree of mobility.

5.4.2 Dynamic positioning (DP)

Alternatively, a structure can be kept in position by means of a dynamic positioning system, consisting of a multitude of computer coordinated thrusters, capable of holding the seastead in place. This will work regardless of water depth, and (unlike a mooring system) will allow for a lazy station keeping option.

However, such a system will demand a continuous energy input, depending on the external forces.

In order to estimate the costs involved in station keeping, the current, wind and wave loads will be modeled by a continuous 1 knot equivalent current (modeling the effects of current, wind and waves: time averaged, the effect of currents will dominate). There are definitely locations where this is overly optimistic, such as in the middle of oceanic currents, and some where this is overly pessimistic, such as in the center of a gyre. The former can be avoided, but it is not clear that the latter are situated in any otherwise suitable locations. Given the many constraints on geographical location, it seems unlikely that an optimally still location is available, but less than one knot on average should certainly be possible.

The ClubStead metocean data notes the current speed during the 1-year storm as roughly one knot, so the current will hardly ever exceed one knot. These currents are all assumed to be wind-driven, so during less wind, as is typically experienced, the currents will be proportionally less too. This does not account for any global current, or other external forces. For the ClubStead mobility scenario, a 2-knot countercurrent is assumed. This seems on the high end, but no motivation is given.

It is noted that current drag varies as the square of the current speed, and that the power required to overcome this drag is roughly proportional to the cube of the current speed. Hence, doubling (or halving) the average current speed will increase (or decrease) power required (and fuel cost) by a factor of about eight; that is to say, by nearly a full order of magnitude, assuming current is the dominant component of drag force in normal wind conditions.[21,22,23,24]

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[21] http://oceancurrents.rsmas.miami.edu/

[22] http://seacoos.org/Data%20Access%20and%20Mapping/Currents_product_desc/

[23] http://sampit.geol.sc.edu/Wera%20maps.html

[24] MINIFLOAT: A Novel Concept of Minimal Floating Platform for Marginal Field Development, p540

5.5 Cost of energy

In order to estimate the cost of mobility in dollars, in this paragraph, an estimate of the cost of energy on the sea is made. This estimate assumes the use of diesel fuel. Bunker fuel is considerably cheaper, but can only be applied in large seasteads due to the required capital investments. Also, when not in international waters, restrictions will probably apply on the burning of such polluting fuels. For the same reason, it might not be a good solution for the long term, as a large community running on bunker fuel would probably face real pollution issues. Natural gas is another option with lower operating costs than diesel. However, diesel is a conservative choice, due to its wide availability and reliability.

- The cost of marine diesel[25] is estimated at $4/gal at quayside. The cost delivered to a platform will obviously be greater, depending on the location and distance from shore-side fuel depot.
- Diesel weights 7.15lb/gal
- One short ton equals 2000 pounds
- Thus, the cost of marine diesel is: 4 * 2000 / 7.15 ~= $1200/st
- One short ton of diesel can generate 5MWh of electrical energy (ClubStead report)

Estimated cost of a diesel generated kWh: $1200 per st of diesel, equals 5MWh, or $0.24 per kWh.

The average cost of electricity[26] from the grid: $0.10/kWh

Therefore, electricity comes at a premium on the sea: accounting for some variability in fuel costs and transportation costs, it is easily three times as expensive as on land.

Propellers can be very efficient in optimal conditions but due to the low velocities under consideration, efficiency will likely suffer. For the electric-to-fluid conversion, an efficiency of 60% is assumed, which is on the low end for non-cavitating propellers, and seemingly appropriate in this regime.

5.6 ClubStead review

The ClubStead report contains some calculations with regard to mobility. They will be reviewed here, to provide some clarification and to establish a reference point for comparison with other designs.

> **ClubStead mobility scenario**: 2 knot movement against a 2 knot current 25% of time, for a 4 knot velocity relative to the water.
>
> **Outcome**: propulsion operational expense (OPEX) 1700st of fuel per year, or roughly twice the expected utility OPEX of 750st per year

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[25] http://www.psmfc.org/efin/data/fuel.html#Data

[26] http://tonto.eia.doe.gov/energyexplained/index.cfm?page=electricity_factors_affecting_prices

This level of mobility does not provide much beyond station-keeping ability. In fact, if the 2-knot current acts all the time in roughly the same direction, moving at 4 knots 25% of the time does not even suffice to maintain position. However, the origin of this 2 knot current is unclear, and inconsistent with the one knot maximum current derived in the metocean section of the ClubStead report.

The utility OPEX is in the ClubStead report derived as the total American national electricity consumption divided by its population. However, this is a much higher number than merely domestic electricity consumption, which is arguably the more relevant number.

The American *per household* consumption[27] should be slightly *lower* that the American *per person* consumption used in the ClubStead report. At 2.6 people per American household, the relative comparison of the mobility costs and utility costs in the ClubStead report is off by roughly a factor three, if utility OPEX is interpreted as stated above.

The propulsion cost estimate provided in the ClubStead report contains some mistakes; after some discussion with the authors, these have been worked out but the corrections are not included in the published ClubStead report. Adjusting for these corrections, and accounting for propeller inefficiencies, a fuel consumption of some 4500st of fuel per year is arrived at: almost a factor three higher than the original figure. Using the utility consumption estimate lowered by a factor three, and increasing propulsion consumption by a factor three, the gap between utility and propulsion energy consumption becomes a worrisome factor 20. Given that as established above, off-grid energy is not cheap to begin with, this is reason for concern.

Translated to dollars, a figure of $1600 per person per month in propulsion cost alone is obtained for this scenario (four-knot velocity relative to the water, 25% of the time), assuming full occupancy. This might be acceptable for a high cash flow operation, such as a casino, but for residential applications, this is almost certainly prohibitive.

When subjected to the continuous 1 knot current scenario, the fuel costs per person per month would be $100. This is an acceptable figure, but not overly so: it assumes full occupancy and current fuel prices, neither of which can be guaranteed. For a household of several people, it is still very conceivable that mere station keeping costs might become prohibitive. On the other hand, the 1-knot current scenario might well be pessimistic; establishing narrower bounds on the current scenario is worthwhile.

Furthermore, it should be emphasized that ClubStead is not optimized for mobility; these results need not be representative for semi-subs as a whole, and could conceivably be much improved upon (although not within the ClubStead paradigm of separate columns without a continuous underwater pontoon; a semi-sub with a streamlined underwater pontoon would be required, as is common in semi-subs with propulsion. For more information see the section on semi-subs in part 2 of this document).

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[27] http://wiki.answers.com/Q/How_much_electricity_does_the_average_American_household_use

Either way, these figures established a reference point to draw comparisons with. The station keeping costs of ClubStead are borderline acceptable in the context of the 1-knot current; an order of magnitude higher would clearly not be, an order of magnitude lower clearly would.

5.7 FPSO Station keeping costs

In (Aalbers, 2006) a comparison of fuel consumption is made between a passively-moored Floating Production Storage and Offloading Vessel (FPSO) and a Dynamic Positioned FPSO.[28] The vessel measures 260x46m, and has around 200kT displacement. The location investigated is the Gulf of Mexico, which does not have strong currents; current strength rarely exceeds 1m/s, or 2 knots, and will typically be considerably lower. Exactly how this compares to the 1-knot current scenario is not clear, but it should be within the same order of magnitude.

The difference in total fuel consumption (including all uses of power) between the DP and moored versions is only 100.000€ per year. Therefore, the annual cost of operating the DP system is 100.000€.

A seastead of the same size as the vessels considered in this document could easily house hundreds of apartments, which would result in station keeping costs of around 15€ per apartment per month; a trivial cost.

It should be noted that this is a large vessel, and benefits from the positive economies of scale inherent to shipping costs; in the calculations, bunker fuel is assumed rather than diesel. However, it serves to illustrate the fact that station-keeping costs are not a limiting concern for displacement hulls of ship or barge type, and that there is a large difference between them and other concepts in this regard.

Diesel/bunker-electric propulsion has been assumed in this analysis, as it is the standard by which dynamic positioning systems operate; any less flexible mechanism would be unable to provide the maneuverability to operate a large amount of seasteads in close proximity.

Since the operating costs associated with fossil fuels are substantial, a search for a more cost effective solution is tempting. However, they are the current standard; therefore, the burden of proof is superior costs is considered to be on the alternatives, which should include consideration of capital, operating and labor costs. No convincing alternative has been identified so far.

5.8 Force calculations

Exactly predicting the force on a moving or stationary body is very complicated, but a simplified model will suffice for the purpose of performing a feasibility study.

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[28] AALBERS, Albert B.; DE VRIES, Leo; VAN VUGT, Hans. Fuel consumption and emission predictions: application to a DP–FPSO concept. Houston: Dynamic Positioning Conference, October 2006.

Only low speeds relative to the water will be considered. The external force components are due to current, waves and wind. For the present analysis, only a single seastead will be considered, and possible interaction effects will be ignored.

By wave forces, second order wave drift forces are meant: the net time average force caused by a wave, as this is relevant for station keeping and mobility, whereas the cyclical component is relevant for comfort and structural integrity considerations only.

Wind forces are found to be small relative to these other forces for high-drag structures such as semi-subs; they can be significant for a more hydrodynamic ship-like design (wind is noted as up to 50% of resistance for big container ships at cruise speed, but their mobility costs are better estimated from available empirical data, if desired, rather than from ab-initio methods.

5.8.1 Drag force

Drag forces can be calculated by means of a quasi-empirical relation: $F=½ \rho C A v^2$

The meaning of A and C, area and drag coefficient respectively, vary by context. For streamlined bodies at low speeds, such as ships, A is the wetted surface area, and C is a coefficient whose value is far smaller than one. For ships and ship-like structures, drag forces are believed not to be limiting, so this is of comparatively little interest.

For blunt bodies such as cylinders, drag is calculated relative to the projected area. The drag coefficient is a function of the velocity and diameter (Reynolds number), and can be looked up in a table. Drag coefficients for cylinders in the region of our interest turn out to be bounded from above by one, and bounded from below by 0.5. Generally, they are closer to one and hard to estimate. A factor of 0.7 is suggested[29], but this is for an arguably higher Reynolds number. To be on the safe side, a factor of one is used: the same conservative approximation is made in the ClubStead report calculations.

This is sufficiently accurate to model the drag on moving spars and semis, although the latter might have significant horizontal area, and interaction effects between the multiple vertical columns that are ignored in this analysis. However, these effects are believed to be small enough not to be worthy of more detailed study at this point.

Wind drag can be estimated by similar semi-empirical relations, but has not been found to be a significant contributor at moderate wind speeds.

5.8.2 Wave drift force

Wave drift forces are forces due to the reflection or absorption of waves. This can be understood by analogy with particles reflecting off the surface, or by analogy with electromagnetic waves. The waves carry momentum, and a change in their direction will cause a reaction force.

Calculating the magnitude of wave drift forces on general structures is a complicated matter. A worst case estimate can be obtained by assuming pure reflection of all waves along the waterline. This is a good approximation for large floating islands facing the waves perpendicular to their direction of propagation. The force per meter of structure in this scenario[29] can be found from this equation: $F = \frac{1}{2} \rho g A^2$

This force is quadratic in wave amplitude A; thus of little concern in calm seas, but potentially the dominating factor in rough seas. For larger structures and stormy conditions, this force component is dominant[30], exceeding current drag forces by an order of magnitude. Station keeping by mooring is difficult for large floating structures[30], and would be impossible or prohibitively expensive in deep waters. Only lazy station keeping would be possible for such a construction; accommodating the worst case wave drift forces would require up to 10mt of force per meter of exposed waterline. By comparison, a large, 10m beam tugboat, is capable of delivering 100mt of force. This illustrates quite clearly that accommodating this worst case scenario is unlikely to be economical in terms of capital costs: a lot of engine power would be required that would under normal circumstances be completely useless.

The force on a cylindrical structure is less than derived from its projected waterline area, or diameter, the force on a cylinder being $F=1/3\rho g A^2 D$, reflecting the fact that the waves scatter off in all directions, and are not all completely reversed.

Significant reflection only occurs when the wavelength is not big relative to the structure. A cylinder of one meter diameter will hardly reflect any waves, and will not experience much in the way of wave drift forces. The typical wavelength of energetic waves in the open ocean is in the 50-200m range. Objects whose principal dimension is an order of magnitude smaller than this will be nearly unaffected. Similarly, a big but slender (ship-like) structure oriented into the waves will experience only modest wave drift forces, due to reduced frontal area in the direction of the waves.[31]

5.8.3 Interaction effects

Wave drift forces depend on wave transmission, or lack thereof, and since wave transmission is a complicated matter, so are wave drift forces. Even though a single column is nearly entirely transparent, reflecting only a small fraction (say, 1/m) of wave energy, this does not mean an arrangement of n columns will reflect merely n/m. [32]

In fact, an array of columns is entirely opaque to some wavelengths, related to the spacing between these columns.

Experimental studies find wave drift forces on a semi-sub VLFS, which presents an array of columns to the waves, to be up to half the force experienced on a similarly sized pontoon system[33], which nearly completely reflects the waves. While this represents some reduction of force, it is still of the same

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[29] http://www.wikiwaves.org/index.php/Wave_Drift_Forces

[30] http://www.offshoremoorings.org/moorings/2005/Maas/index.html

[31] Ocean Energies, Roger Henri Charlier, John R. Justus, Elsevier, 1993

[32] http://www.isope.org/publications/journals/ijope-11-3/ijope-11-3-p176-abst-CH-45-Kashiwagi.pdf

undesirable order of magnitude. In (Hiraishi, 2007)[33], the distribution of force between the individual columns is not measured; it is unlikely all columns experience the same forces; in fact the absorption/reflection will mostly go on in the first ranks of columns. Thus instead of providing a homogenous translating force, these forces will tend to push a spar forest into itself, leading to either high loads on connection systems, or if considering a forest of individual spars, excessive requirements for the dynamic positioning systems of the first rows of seasteads facing the waves.

A semi-sub, having multiple columns, might be suspected of experiencing significant wave drift, however, as the typical semi-sub has merely four columns, wave drift forces are found not to dominate over current and wind loads[34], making up only about 10% of total forces during a storm.

6 Waves

Probably one of the most challenging aspects of seasteading is dealing with waves; surviving them, and operating comfortably within them. Hence, some understanding of waves and their effects is required to be able to understand what constitutes a good seastead design, and what limitations are to be expected.

6.1 Phenomenology

One of the problematic properties of waves in the ocean is that they may become almost arbitrarily large. There is no physical limitation on the maximum wave height one might encounter. Waves in the ocean are primarily generated by wind, which needs to blow over long distances to produce significant waves. This poses some constraints on the maximum energy contained in the water.

However, one complicating factor is that this energy is distributed stochastically. If multiple wave crests happen to converge on one location, a single large wave may result. Large waves far out of the prevailing pattern of waves are known as rogue waves. They are believed to play a significant role in the number of ships lost every year, and have been known to cause damage to oil platforms and ships. These rogue waves present a significant challenge for the reliability of seasteads.

It should be noted that waves in the open ocean behave rather differently from waves that come up to the beach. Waves in the open ocean are much more flat, and under normal circumstances, do not break.

6.2 Mathematics

The wave theory considered here is limited to linear deep water gravity waves, i.e. linear in the sense that ‘small’ amplitude waves will be considered, and neglecting nonlinear effects, such as for instance the

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[33] Directional Random Wave Experiments on Motion and Mooring Force of an Elastic Floater", **Tetsuya Hiraishi**, Port and Airport Research Institute, Yokosuka, Japan; Journal of Ocean Technology, volume 2, number 3, 2007 http://www.journalofoceantechnology.com/?page_id=73&id=5&jot

[34] http://www.isodc.com/1st_ISODC07_TexasA&M_Team_3_SemiSub_for_Malaysia.pdf

breaking waves. ‘Deep water’ refers to the fact that the influence of the bottom is neglected; this is a very reasonable assumption provided the water depth exceeds one-half the wavelength of the longest waves considered. ‘Gravity’ refers to the restoring force associated with the waves.

By the assumption of linearity, any sea-state may be regarded as being composed of a superposition of sinusoidal waves. The surface profile of a traveling wave can be described by $h=A \sin(kx-\omega t)$, where x and t are space and time coordinates, k and ω are the wave-vector and angular frequency respectively, and A is the amplitude.

These quantities can be shown to be related as: $\omega^2=gk$

Subject to the standard wave relations, $T=2\pi\omega$, $f=\omega 2\pi$, $\lambda=2\pi k$, $c=\omega k$

Thus, every wavelength has a different speed of propagation, a characteristic of deep-water waves.

Waves do not merely act on the surface, but their effect extends into the water. The relation between depth and amplitude of a wave is exponential, and may be represented as a function of depth and wavelength (or wave-vector) as $A(z)= A \exp(-k z)$. Thus, the effect of a wave diminishes quickly with depth, and shorter waves decay faster than longer ones.

This results in a complete solution for a single wave component in terms of position, depth and time[35]:

$u=\omega A \text{ cosine } (k x - \omega t) \exp(-k z)$

$v=\omega A \sin (k x - \omega t) \exp (-k z)$

$p=\rho g A \text{ cosine } (k x - \omega t) \exp(-k z)$

where u and v are horizontal and vertical velocity components, and p is the pressure disturbance due to waves (not including hydrostatic pressure).

One relevant yet not intuitively obvious result is that a given patch of water tracked through the motion of a gravity wave makes circular motion. Objects floating in water not otherwise disturbed will move as much laterally as vertically.[36,37]

6.3 Sea-state

The above section treats monochromatic waves. The actual waters of the sea can be thought of as a linear superposition of such waves, of varying frequencies and directions.

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[35] http://folk.ntnu.no/oivarn/hercules_ntnu/LWTcourse/lwt_new_2000_Part_A.pdf

[36] WikiWaves.org

[37] http://www.ocean.washington.edu/people/faculty/parsons/OCEAN549B/lwt-lect.pdf

The distribution of frequencies is in general not completely arbitrary, but follows a distribution clustered around a dominant wavelength. This spectrum is typically characterized by two parameters; the 'significant wave height', H_s, and the peak period, Tp.

Formally, $H_s(1/3)$, or H_s for short, is defined as the average height of the highest third of wave crests. Instead of using the complete spectrum, in this report analysis proceeds by a simplified monochromatic wave matching the parameters of the dominant component of the spectrum. This is of course a simplification: some crests may be far higher than H_s; in fact, a wave of nearly twice H_s occurs with a probability of 1/1000. But beyond this amplitude, probability diminishes significantly.

Often, a sea-state is composed of locally generated waves, and the residual waves of a storm in the distance. This latter component is referred to as swell, and typically has a low frequency. If the swell comes at an angle to the wind generated waves, the resulting sea is called a cross sea. Such conditions are potentially hazardous to ships, because the hull cannot be aligned in two directions at once.

One aspect of open-sea waves that is typically underestimated is their length; again, waves coming up to the shore are not representative, as in the process of running up on the shore, their wavelength is compressed. On the open sea, the dominant wavelength may be up to hundreds of meters.[38]

7 Wave-interaction

7.1 Forces

The continuous motion of waves causes stresses in a vessel in various ways. The relevant ways in which the water can stress a seastead are discussed here.

Where considerations of strength are limiting, a minimum design safety factor of two or more may be appropriate. This is a fairly arbitrary choice; design loads and safety factors are specified in detail by the relevant standards established by classification societies such as the American Bureau of Shipping (ABS), Lloyds Register (LR), Det Norske Veritas (DnV) and the like.

With regard to rogue waves this would imply the following: given a sea-state with H_s=8m, waves with a height of twice H_s will occur with a frequency of approximately one in thousand wave crests. Beyond this height, frequency drops off rapidly, and this height of twice H_s is chosen as a design basis. However, rogue waves far higher may occur. Prediction of rogue wave occurrences and statistics is currently an area of active research in the ship structural design community, and beyond the scope of this research paper. However, the potential occurrence of rogue waves is something that will have to be dealt with in the design of any seastead that is intended to be deployed in the open ocean.

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[38] http://en.wikipedia.org/wiki/Sea_state

7.1.1 Hydrostatics

One component that must be taken into account when designing a seastead is hydrostatic pressure. Pressure increases with one atmosphere for every ten meters below the water. It may be a dominant factor in the design of spars, and is a significant component of load in all floating structures.

Submersible vessels are loaded predominantly by hydrostatic pressure, and those pressures can become substantial in designed for very deep submergence. Submarines that might be considered as candidates for the purposes of seasteading will not go to great depths (50m at most); overcoming these forces is not a big problem, and due to their predictability should be accomplished with a high degree of reliability.

7.1.2 Hydrodynamics

The hydrodynamic forces are the result of moving water, i.e., waves. They can be broken down into several phenomena

- **Breaking/Slamming**: typically, the interaction between a wave and a structure is a continuously varying process; the water level gradually rises and falls. However, if the waves become very steep (and possibly break), or a surface of the vessel is non-vertical (such as the bow of a ship), a waterfront can suddenly impact upon a large area, causing a spike in force experienced by the vessel.

  However, in the open ocean, waves do not break completely, only partially during severe storms. As a rule of thumb, the height of a wave cannot grow beyond one fifth of its wavelength (without running up on shore), severely restricting the maximum wave slope which might be encountered. Classification societies provide abundant guidance for estimating these types of impact loads.

- **Horizontal forces**: A vertical column in the waves, at rest relative to the bottom, experiences a horizontal force, which can be calculated using Morrison's equation. This force consists of two components: one due to drag of the water moving around it, and one due to the acceleration of the displaced water. If the column were not otherwise fixated, it would move and accelerate with the waves; since it is not accelerating, a force proportional to this acceleration is required to keep it in place. The combined effect can be very large under worst case conditions, and complicates the interconnection of seastead designs based on vertical columns, such as spar and semi-subs.

- **Hogging/sagging**: this is the primary concern for vessels of large horizontal extent, such as ships and floating-island type designs. As a hypothetical extreme of sagging, one could imagine a ship being lifted out of the water at its endpoints by two wave crests, and losing its support along its middle. This introduces a large bending moment in the vessel; instead of being supported by the water, the vessel will have to be capable of carrying nearly all of its own weight, like a bridge. Hogging is a bending in the opposite direction; whereby the vessel is lifted by a wave crest somewhere at its center.

  The American Bureau of Shipping (ABS) classification standards specify the bending moments a vessel must be able to withstand over a range of parameters[39]. Magnitude of bending moment increases roughly in proportion to the vessel's length-squared, which suggests the difficulty of constructing increasingly long vessels.

7.2 Motion

This section tries to shed some light on the physics of wave-induced motion. Wave induced motion is a big problem for seasteads, and a driving concern in the overall choice of a concept. Some understanding of the mechanisms whereby a vessel moves or remains stationary is therefore useful.

7.2.1 Response Amplitude Operator (RAO)

In general, floating structures do not perfectly follow the waves; the degree to which their motion matches that of a wave of a given frequency is captured by the notion of a response amplitude operator (RAO), which specifies the ratio of motion response to wave amplitude for all frequencies. A RAO of unity in heave at a certain frequency means the structure will exactly follow the amplitude of the waves at that frequency. In elongated structures, such as ships and spars in particular, the linear motion response at an extremity is a function of both the translational and rotational degrees of freedom. For instance, even if a ship has insignificant heave at its center, this does not preclude large vertical motions at its bow and stern due to pitching motion.

The computation of entire RAO's is a complicated process, requiring specialized software that is expensive and not easily obtained or reproduced; no free alternatives have been identified. All RAO's considered in this report are drawn from external sources.

7.2.2 Resonance (Natural Frequency)

One of the important characteristics of a RAO is its resonant (or natural) frequency. At frequencies far above resonance, response amplitude will tend to zero; at frequencies well below resonance, response amplitude will tend to unity. If possible, it is most desirable to have the resonant frequency well below the frequencies where wave excitation is prevalent; i.e. to ensure that wave excitation will occur at a frequency much higher than the resonant frequency, so that the response will be very small. This is sometimes referred to as "surface-piercing" behavior, wherein the vessel is effectively de-coupled from the sea. This is the principal behind the design of semi-subs and spars.

For conventional hull forms (ship and barge shapes) it is not feasible to achieve a "surface-piercing" type of behavior; in those cases it would be desirable to have the resonant frequency be much higher than the predominant wave frequencies, so the response will tend to unity. In the limit, this is sometimes referred to as "surface-following" behavior, wherein the vessel follows the height and slope of the sea surface; however this condition is only achieved for very small vessels in very large waves, i.e. where wave length is several multiples of the vessel's length. For conventional hull forms, it is difficult (if not impossible) to avoid circumstances where wave excitation will occur at the vessel's resonant frequency.

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[39] Probabilistic presentation of the total bending moments of FPSO's

Calculation of resonant frequencies is fairly straightforward for spars and semi-subs, it follows the same logic as the classic harmonic oscillator: frequency in radians per second equals the square-root of restoring force stiffness over inertia; $\omega^2=kM$. For the heave period, we have $\omega = g A V + V_a$, with g the gravitational acceleration, A the waterplane area, V the displaced volume, and V_a the added displaced volume (density divided out). Since having low angular frequencies is desirable, this condition translates into a low water-plane area and a high total displacement being desirable. Thus the good heave performance of a spar and semi-sub. For ship-like structures, heave response is harder to calculate.

7.2.3 Horizontal extent (Length and/or Breadth)

One way of influencing the motion response of a vessel is by means of altering its horizontal dimensions. Qualitatively, the relation can be understood easily: the motion of a structure bears a resemblance of the average motion of the displaced water. Hence, if a vessel is big relative to a wavelength, its response to that wave will tend to zero.

Obtaining a quantitative relation between these parameters is more difficult. If a structure is less than half a wavelength in extent, it will tend to mostly follow that wave; if the structure is more than twice the wavelength, its response will tend to zero. In between these asymptotes, behavior is harder to predict, and will depend quite strongly on the position on the vessel under consideration.

Given that the range of wavelengths in the open ocean with significant amplitude are in the 100-300m range, it should be clear that designing a vessel that is insensitive to the whole of this spectrum by means of its horizontal extent requires a very large structure indeed.

It should be noted that the relation between horizontal extent and motion response is far from linear. Doubling the size of a ten meter vessel will not 'double' comfort, but will in fact make no significant difference relative to the wavelengths encountered in international waters. Both are still 'small' relative to a wave of 100m in length. Horizontal extent begins to affect wave interaction more significantly when it exceeds wavelength.

Horizontal extent has two dimensions, width and length. To obtain a low response to all kinds of waves regardless of orientation, an island-type seastead of hundreds of meters in diameter would be required. However, in practice, the benefit of such a strategy over a long and narrow, or ship-like shape are likely non-existent; by a combination of orienting the elongated structure into the waves, and possibly active roll-stabilizing tanks, a similar motion performance can be achieved.

7.2.4 Vertical Extent (Depth or Draft)

Within the confines of linear wave theory, predicting the motion of a volume of water in waves is a solved problem. As noted in the mathematical treatment of waves, the pressure variations associated with their action decays exponentially with depth. This suggests that diving below the wave surface is a good way of avoiding them, as every surfer knows.

- **Submerged**: The motion of a patch of water in a wave is known; from this, predicting the motion of a rigid body displacing said volume of water, and having the same average density, follows to good approximation. As long as the water deforms little (dimensions small relative to the wavelength), the rigid body will do ‘almost’ the exact same thing as the water it is displacing would have done.

This is an excellent way to predict the motions of a ‘single family submarine’, and for bigger submerged structures, it is a conservative approximation; different parts of the submarine would want to do different things in absence of the rigidity of the submarine, and the net effect will be an averaged one. Using this method, one can for instance show with a high degree of certainty that comfort will be guaranteed for any kind of storm, for a vessel submerged as little as 30m; for more typical sea-states, far less will suffice.

Submarines provide a conceptually easy way to provide comfortable living space, but they have many drawbacks of their own, related to living below the water. Having the floatation below the waves and the topside above the waves seems like a good resolution. The problem of stabilizing such a configuration naturally leads to two different seastead concepts: the semi-submersible and the spar.

- **Semi-Submersible**: A semi-sub consists of a pontoon located at some depth below the waves, and an upper deck supported by multiple columns that extend well above the surface. In order for the configuration to be stable, these columns need to be spatially separated, so that a restoring moment will be generated as the structure undergoes some angular displacement.

  This has a few unavoidable consequences. First of all, a semi-sub needs to be of considerable size in all dimensions: it needs both distance below the waves to obtain low motion response, and distance above the waves to provide a big enough air-gap, to avoid wave damage to the topsides. Further, both horizontal dimensions need to be on a proportional scale, in order to provide a stable whole. The considerable minimum size required in all three dimensions (approximately 30x30x30m) leads to a large minimum realizable displacement for a semi-sub.

- **Spar**: Another way of making a pontoon-topside combination stable is by means of lowering its center of mass. This naturally leads to the spar concept. A spar is a very slender design, but it needs to extend deep into the water to obtain good motion performance. The section providing the displacement force (the ‘hard tank’) will need a certain volume to provide sufficient floatation. Since considerations of natural periods demand it be slender, this implies it needs to be long; at least some 30m deep. In order to balance the whole, the ballast will need to be located some 30m lower again. This leads to a structure extending at least 60m below the water; the shallowest draft spar in existence, FLIP, has a draft of 90m. These claims will be explored in more detail in the spar section; but summarizing: making use of depth in this way to obtain good motion leads to constraints on scale as well. However, because a spar needs to be big in only one dimension, the minimum scale is more favorable than a semi-sub.

  Further, it should be noted for both semi-subs and spars that due to the columns connecting pontoons and topsides, the total interaction with the waves will be increased relative to the pontoon in isolation. Especially horizontal motions (swaying) might be problematic for these concepts, which are not much of a concern for a ship or submarine.

There are more subtle ways of influencing motion performance, the flaring diameter of FLIP being one example. Seen from the bottom, it has a bigger wetted area than seen from above. Since wave disturbance decreases with depth as a function of wavelength, there exists one wavelength for which the upward and downward pressure fluctuations cancel out. This zero in forces is engineered to coincide with its natural period. Though this effect plays a subtle role in semi-subs as well, only a very deep structure like a spar allows for large enough differential-depth effects for this to be significant.

One interesting concept for minimizing interaction with waves is known as indirect displacement. Examples of this technique are the Pneumatically Stabilized Platform (PSP), or hovercraft. The idea is to transfer the weight of the structure to the water through a column of air. This provides an element of cushioning, thereby effectively decoupling the structure from the waves. The PSP is the more practical implementation of this concept, but suffers from some concerns. The open cell structure at the bottom is expected to lead to very large drag forces, and it is not obvious that this open and complicated structure can be reconciled with the large bending strength that is required to withstand hogging and sagging moments in the open ocean.

7.2.5 General Observations

In between these physical effects, all known ways to significantly affect motion performance have been discussed. Regardless of the chosen path, there is a common relation; all strategies are size dependent.

By thinking in terms of these physical principles, rather than specific designs, a more general view is offered, and many superficially different design concepts can be viewed as variations on a theme, or intermediates between archetypes. This allows a more succinct view of the spectrum of possibilities; rather than wondering about the wave response of each individual proposed concept, a quick impression of every concept, given its main features, can be made.

Active systems may contribute to improved motion response. One can conceive of mechanical contraptions, but they are likely impractical in the harsh ocean environment, as well as with regard to energy requirements.

The passive systems with a proven track record are stabilizing gyroscopes, which act to counter any overturning moment and anti-rolling wave tanks, containing sloshing water in anti-resonance with the external waves. Both are effective only against rolling motion. Either a passive or an active system significantly affecting heave seems inconceivable on first principles, because the associated forces of fluctuating buoyancy are very large.

8 Comfort

8.1 Motion sickness

One often encounters the notion that heave motion is the dominant contributor to motion sickness. Yet considerable disagreement as to the exact causes is found in the literature, not only as to the magnitude of these effects, but also the relevant metric by which to asses them, and the relative significance of vertical, horizontal and rotational motion.

ISO standards for both vertical and horizontal accelerations exist, but it should be noted that the perception of comfort is not an exact science. The horizontal acceleration criteria are derived in the context of the sway of high rise buildings. Some information is reviewed in. Based on that, the following conclusions are drawn:

- Recommended maximum RMS acceleration for offshore structures is 0.40m/s^2.
- Recommended maximum RMS acceleration for general purpose buildings is 0.07m/s^2.
- 0.2m/s^2 is noted as the limit where desk work becomes difficult, nausea starts.

The ISO limit on vertical acceleration is defined as conditions which on long term exposure will result in motion sickness in more than half of passengers on a ship, where 'motion sickness' is defined by the objective physical signal of vomiting (not just subjective discomfort, this may be far higher).

- ISO limit RMS horizontal acceleration[40]: 0.25m/s^2

It is not clear that this data supports the notion that vertical acceleration is indeed more critical than horizontal acceleration. The 0.25m/s^2 horizontal limit is defined as provoking strong nausea, involving throwing up, whereas 0.20m/s^2 vertical acceleration leads to mere mild nausea. In addition, a spar platform (and under some circumstances, a semi-sub) has stronger horizontal response than vertical response, thus for these structures, the horizontal motions may in fact be limiting.

This horizontal exposure limit is based on data for non-mariners. It is frequently remarked that people experience strong adaptation to motion-induced sickness; yet this effect is nowhere quantified. (The only quantitative information found is that 5% of people do not experience any adaptation at all).

The large spread between the recommended values for horizontal motion between general purpose and offshore structures might represent an adaptation effect, or a selection effect. Either way, it is a large difference. If such a factor 5-6 difference in comfort could similarly be assumed for vertical motion tolerance, this would greatly reduce any motion sickness concerns. Further investigation of this topic is strongly recommended.[41]

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[40] ClubStead hydroanalysis report

[41] http://www.cppwind.com/support/papers/papers/structural/PEAKvsRMS.pdf

8.2 Methodology

Detailed prediction of motion performance is a costly and concept-specific process that is not justified given the level of the present investigation. The present methodology for assessing comfort is based on simplifying all seas to an equivalent monochrome wave of comparable properties.

A particle moving in sinusoidal motion as $A = \sin(\omega t)$, experiences a peak acceleration of $a = A \omega^2$, which corresponds to a RMS (root mean square) acceleration of $A_{RMS} = A \omega^2 / \text{sqrt}(2)$. The RMS of acceleration is commonly used as a measure to describe a 'quantity of motion'. By evaluating the RMS acceleration for some worst case scenarios in this way, an adequate impression of overall motion response can be obtained.

8.3 ClubStead metocean

The most detailed metocean data available is found in the ClubStead report. From the various numbers encountered in reading, it can be concluded that ClubStead metocean conditions are particularly gentle for a (near) international water location. The main bodies of the Mediterranean or Baltic experience similar worst case conditions, of H_s~=8m. As far as issues of comfort are concerned, worst case conditions may be considered to be H_s=5m; these waves occur with a frequency of 3.2% of the time. Higher waves occur less than one percent of the time (only ~3 days per year); violations of comfort of a similar frequency are considered to be non-prohibitive for the purpose of building a society, thus the long tail of events worse than these are ignored. For these H_s=5m waves, a typical peak period is Tp=14s.

8.4 Example calculations

As an example calculation of motion sickness, perfectly following the motion of these (Hs=5, Tp=14s) waves, as one would in a small boat for instance, would incur 0.35m/s^2 RMS acceleration both horizontally and vertically, far above the limit for either vertical or horizontal motions. As such, having sub-unitary response at this frequency is important.

Looking at the RAOs found in the ClubStead report, we see that heave response at this frequency is minimal. Yet surge response at this frequency is roughly 2/3, leading to a total acceleration still above the 0.20 limit; and this ignores the compounding effects of roll and pitch that will increase topside motions.

The longest swell ever experienced in the ClubStead scenario would not break the ISO limit on vertical motion even if occurring at its maximum amplitude and followed exactly with unit response, due to the longer period translating into lower accelerations. (Tp=20s, H_s=4m, λ =270m)

This demonstrates that amplitude is far from everything as far as discomfort is concerned; the waves potentially most affecting comfort are the shorter waves, due to their higher frequency. The waves in the ClubStead scenario having the most compromising combination of length and amplitude are around the (Tp=8, H_s=4m, λ=90m) range. A swell having these properties, followed exactly, would lead to a RMS acceleration of 0.9m/s^2, or ~1/10th g. It is imperative the structure has very little response to these kinds of waves. Spars and semisubs of any kind will satisfy this requirement. As can be inferred from the wavelength, a 200m long hull in head seas would be strongly sub-unit (<< 1.0 RAO) excited by these waves, since it is far larger than the wavelength. As can similarly be inferred from the existence of longer waves of up to 300m in length, achieving such an effect over the entire spectrum requires a rather long structure.

Further, it illustrates just how badly the ISO limits can be exceeded for smaller vessels in the open ocean. Any vessel with dimensions not exceeding half this wavelength (~40m) in any direction will tend towards unit response to these kinds of waves. Shorter waves would compromise comfort for such a structure even when only one meter high.

9 Modularity

9.1 Introduction

The Seasteading Institute does not aim at enabling the creation of a single isolated seastead, but rather a city that can grow according to demand. As such, all concepts will need to facilitate the possibility of moving goods and people between them. This is especially true for smaller seasteads; when living on a hypothetical single family seastead, moving to other seasteads will be a daily need. Summarizing, modularity here refers to all issues related to the transfer of goods and people between seasteads.

9.1.1 Direct vs. Indirect

Two different ways of accomplishing these goals can be distinguished: direct or indirect transfer. Indirect transfer here means transfer by means of an intermediate vessel, as opposed to direct transfer, which is between two seasteads. Indirect transfer is also transfer, and thus encounters the same problems; the problem of transfer is dealt with first, and the peculiarities of indirect transfer are treated afterwards.

9.1.2 Bridging

The problem of modularity can be regarded as consisting of two steps: creating a walkway between them, and in order to achieve this, retaining the vessels in some more or less fixed relative position.

An example of a bridge between vessels is provided by the Offshore Access System (OAS).[42] Its intended purpose is to facilitate the transfer of people between oil platforms and their support vessels. It allows for some relative motion between its points of attachment, compensating for this by means of several degrees of freedom. The range of motions it can handle is limited, and hence its operability is bounded by the sea-state.

Another way of bridging the gap between vessels is by means of a crane. This is primarily used for the transfer of goods. The operability of cranes is quite strongly bound by both wind and waves.

9.2 Relative Positioning

In order for such bridges to be formed, vessels will need to be able to remain in physical proximity without compromising safety. The desired degree of relative position keeping can be attained in three ways: mooring, dynamic positioning, or some form of connections between the vessels.

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[42] http://www.offshore-solutions.nl/en/products__services/the_offshore_access_system_oas_for_heavy_seas

9.2.1 Mooring

The potential for a mooring system to meet this requirement depends on the water depth. In deep waters, a moored structure will always be capable of significantly deviating from its neutral position; up to hundreds of meters. Besides expensive tension legs, other mooring line systems require a footprint with a radius equal to or higher than the water depth itself. This severely limits the potential density of deep-water moored seasteads.

Due to the definition of the EEZ, attractive locations in international waters where mooring is possible may not exist. Hence, outside the EEZ, relative positioning will have to proceed by means other than mooring lines. If mooring is an option, it will be capable of providing quite robust relative positioning, and an OAS-type bridge between the seasteads can be employed.

9.2.2 Dynamic positioning

Dynamic positioning was originally conceived to perform this very task; it is therefore a viable functional solution. The capability of such a system to guarantee no collisions between vessels will depend on the environmental conditions and installed power. Occasional collisions that have occurred between FPSOs and dynamically positioned shuttle tankers suggest that this is not yet a fully-solved problem, but it is the subject of active research within the offshore community and will most likely be resolved long before large-scale seastead communities are realized.

During extreme environmental conditions, a more spread out formation will have to be assumed. However, the system should be capable of maintaining position most of the time; weeks of lack of sufficient operation are not acceptable. One disadvantage of this method is the continuous operating cost. This cost is believed to be small relative to station keeping costs.

9.3 Connections

If seastead modules are constrained by some form of (semi)permanent connection, their relative position will be fixed, and adding a bridge/walkway between them will be trivial.

These connections will have to bear the brunt of the relative wave forces between the vessels, and will therefore have to be of considerable strength. This also implies they will have to be of at least semi-permanent nature, as large, multi-ton and typically welded structures are not easily removed.

In general, it will not be possible to implement connections between existing structures not designed with these connections in mind. Attempting to connect two normal ships in any way, for instance, would introduce forces its load-carrying structure would not be prepared to handle.

By connecting modules into a larger structure, their motion characteristics are altered. The bigger structure will in general be less responsive to waves, more stable, and therefore more comfortable. This provides an additional motivation to connect seasteads into larger agglomerates.

Two subtypes of connections can be distinguished: dense and sparse connections. A dense connection is one where different modules are mated without any spacing, as with Emphemerisle ‘cassettes’, and the connected whole presents a single front to the waves. A sparse connection is one where the individual components are connected by means of some truss or similar structure; the separate legs of ClubStead may be regarded as such modules. Waves will be able to pass through the structure, and the modules may experience large differential forces.

9.3.1 Sparse

ClubStead may be regarded as an example of a sparse modular structure. Some of the difficulties encountered in implementing this solution are discussed in the ClubStead documentation. The core problem is that the individual columns are spatially separated, and thus will experience different wave forces at the same instant. The most problematic component is the horizontal force, which can be found through Morrison's equation. The prying forces thus introduced are hard to constrain; a significant part of the steel budget of ClubStead is taken up by the trusses that link the columns together, precisely for this reason.

Some concepts have been proposed which are essentially even more modular semi-subs (ClubStead is not designed to be extended beyond its 4 columns), but the difficulties encountered in ClubStead would become progressively more prohibitive if the structure were expanded further. No realistic implementations of such a concept have been found, nor do they seem conceivable. A related but somewhat different concept is discussed in the VLFS literature.

Aside from the fact that as such connections are repeated, it becomes more difficult to ensure their integrity; the resulting array of columns would create other problems. The wave-trapping effects of such a grid would result in amplified wave heights, and a wave-reflectance coefficient approaching that of a similar-sized dense structure. In general, it seems as if a dense configuration is more desirable than a sparse one. This may have implications for the choice of hull-type, as attempting to keep a large number of semi-subs in proximity may prove very difficult.

9.3.2 Dense

A dense connection is one where the individual components are mated without any spacing in between them. The Ephemerisle platforms were constructed in such a fashion, and the technique has been used for floating docks. It is also proposed for the PSP platform. This technique is rather different as far as the interaction with the water is concerned. The resulting structure can potentially form a somewhat hydrodynamic whole, benefitting mobility, and differential horizontal forces are of no concern.

The primary challenge in such a connection is resisting the bending moments induced by hogging and sagging forces. If such modules are connected into a large structure, and this large structure happens to be lifted by two wave crests at its endpoints, a very large bending moment results. This is the dominant concern for longer structures, even for monolithic ones, and connections are typically weak spots. If it is possible to design such a construction depends on circumstances; it is not generally impossible, but welding two ships together is never going to work, for instance.

9.3.3 Flexibility

Permitting some degrees of freedom in a connection may be beneficial or even necessary. For both the goals of providing relative positioning and improving motion characteristics, not all degrees of freedom need to be constrained. By unbounded extension of an agglomerate of seasteads into a rigid whole, the potential worst case hogging and sagging forces will continue to increase. By introducing some flexibility, these wave motions may be permitted rather than fought.

An example of this principle can be found in [VLFS base], where an aircraft carrier consisting of several modules connected into a single airstrip is proposed. Motion between the modules is permitted, as a single rigid mile long structure would experience too large forces. The connection proposed in this document seems large and complex, but this is for an indeed very large, mile long structure, which needs to be mated accurately enough for aircraft to land on it. In principle, connecting multiple ships/barges into a train-like configuration should be a very solvable problem, as long as the hulls themselves are designed to carry the associated forces.

A flexible connection system for a spar-like concept has also been investigated in some detail (various variants of the concept presented at the SS09 conference talk by Eelco Hoogendoorn), but the outcome has been found unsatisfying. The worst case forces such a system may experience in the vertical direction are large. This combines poorly with moving parts such as hinges and pistons. Attempts at designing a system that seems plausible technically as well as economically have so far yielded only negative results.

The simple reason why such a system does not add up for a spar-like structure, but should do so for ships connected bow to stern, is that for both type of connections, forces of similar magnitude are at work, but the ship can amortize the forces incurred by a given amount of waterline area over a much bigger volume of useful real estate due to its elongated form.

9.4 Indirect transfer

As opposed to moving directly between two adjacent seasteads, transfer by means of an intermediate vessel might be desirable. These vessels are likely to be small and will consequently have very different wave responses compared to the structure they are attempting to interact with. This will result in large relative motions between the seastead and the intermediate (transfer) vessel. Thus, indirect transfer does not fundamentally ease the problems of modularity; it merely replicates them.

Transfer between vessels in the open ocean is widely recognized as being a difficult problem. Even in very gentle waters during Ephemerisle ‘09, transfer between boats and platforms was often time-consuming and a demanding process. Indirect transfer by small boats may not be practical under most open ocean scenarios.

If these vessels are relied upon for day to day commutes, they should be able to function under nearly all weather circumstances. Adequate mooring preventing damage may be difficult during a storm; simply tying up to a larger vessel will not be possible due to concerns of damage. One possibility would be to bring the transfer vessel aboard the seastead (possibly by means of a ‘launching’ ramp) to simplify the process of loading and unloading the smaller vessel. Such systems are commonly used in large pleasure yachts to launch and retrieve ‘water toys’ and tenders, and could easily be scaled-up to accommodate larger transfer vessels. However, launching and retrieving the transfer vessel still remains a problem in elevated sea states.

Structures of considerable dimensions in both length and width (island-type seasteads), will provide a calm leeward side, but few proposed designs meet that property.

It is implied that this discussion deals with surface vessels (boats). Helicopters likely to provide a better solution; they are certainly expensive, potentially more dangerous, and not necessarily any less sensitive to weather. One interesting possibility is using submarines moving between moon pools; it is an elegant way to eliminate concerns about operability and weather, but for most concepts this will not be an option. It would also require substantial innovation, as this is not how submarines are currently employed.

10 Criteria

In this section, an attempt is made to break down the question of what makes an effective seastead into a set of quantifiable criteria. All concepts that will be considered are judged against these criteria, so that they can be compared along a standardized measure.

10.1 Capital costs

By capital costs, the application-independent capital costs are meant. That is, the hull and auxiliary/support systems, but not the accommodation units or their furnishing. Many offshore structures, including ClubStead, have luxurious accommodations, but these are not essential to the structure design; the focus here is to be on the costs unique to the ocean, such as to minimize the ocean tax.

Specifically, we are interested in the cost per unit area for real-estate on the given platform. For spars and semis, or structures with an air-gap, the topside tonnage which can be supported is the limiting factor, rather than volume or area; we assume an equivalency between those measures as 1/4th of a metric ton per square meter floor area of furnished real-estate, or 4sqm per metric ton. [ClubStead report] Under this assumption, cost per unit area and cost per ton of topside payload are directly related.

Costs will be expressed in fiscal year 2009 American dollars. Where needed, standard inflation correction can be applied.

The target maximum is $2500 per square meter of application-independent real estate. This should be achievable based on the analysis of ships and semis done so far, therefore, scoring much worse on this parameter should not be acceptable unless balanced against other large benefits.

10.2 Mobility costs

Different designs will require different levels of energy input to achieve a given degree of mobility, which will translate into operating costs.

Where given, costs are expressed in 2009 American dollars per person per month. However, translating these costs into a dollar figure is complicated, because of the large number of unknowns involved. Due to uncertainty in fuel prices, uncertainty in forces scenarios, and uncertainty in available space and occupancy rates, the cost per person per unit time can vary wildly. Therefore, a dollar estimate for

ClubStead is performed, and for other concepts, comparisons relative to ClubStead are made, these uncertainties between them being equal.

The costs cited under this category are the cost incurred in station keeping, not including any other maneuvers, subject to the external forces scenario outlined in the mobility section.

10.3 Maintenance costs

These are the maintenance costs independent of application, that is, the hull and propulsion/mooring maintenance costs. This is a function of material use, draft and mobility.

Steel requires more maintenance than concrete, a deep draft hull is hard to inspect, and only the most mobile structures can afford to move into a dry dock for maintenance.

No quantitative measure of maintenance cost is available yet. Positive qualities in descending order of importance are: concrete hull -> mobile/dry-dock maintenance ->shallow draft.

It is not obvious that wet steel maintenance is a realistic option at all.

10.4 Scale

Most concepts come in various sizes, not all of which may meet our design criteria. All else being equal, smaller seasteads are initially preferred to larger seasteads, given that they are more likely to materialize, and provide more fine-grained dynamic geography. Scale is measured by its relevant metric of total hull Capital Expense (CAPEX), in FY2009 American dollars.

10.5 Comfort

Comfort is a subjective requirement. Moreover, designing to deal with the long tail of worst case possible events is expensive; what is the cost differential between a seastead that is uncomfortable a few days a year versus one that is comfortable all of the time? Intuitively, it seems obvious that by accepting short periods of discomfort, one can design a seastead that will be substantially cheaper than one that assures comfort even in the most severe storms. Consider that even in shore-side dwellings, we accept certain discomforts from time to time; typically the loss of electricity and/or communication services due to weather, but occasional disruptions in water supply or other municipal services. At vast expense, it is probably possible to inoculate ones self from any discomfort whatsoever, but people seem to have a pragmatic understanding of the diminishing returns, and are willing to live with occasional discomforts and disruptions in life ashore. Such is likely to be the case amongst seastead communities as well.

Predicting motion performance in detail is an involved process that is not justified at this stage of analysis; moreover, and the mapping between vessel motion and motion sickness is far from completely understood. Therefore, no attempt at making detailed predictions is made. However, a good deal of information can be obtained from the simple method of analysis outlined in the comfort section. This should at least suffice to separate the plausible from the implausible.

10.6 Modularity

This is measured in terms of the ease of transporting goods and persons between adjacent seasteads.

No quantitative measure of modularity can be devised given our current level of detail, but there are obvious differences between concepts in this regard, and a somewhat subjective estimation of this important parameter is therefore made.

This will mostly entail a judgment of two factors: its motion response and scale. Low motion response means easy boarding and increased capability of connections/walkways of some permanence. A large scale structure (aside from having a generally lower motion response) can more easily amortize the cost of sophisticated cranes or walkways over its budget, lowering the modularity cost per person.

10.7 Safety

All structures should meet stringent safety standards, as set forth in relevant international conventions and regulations (SOLAS, IMO, etc.) governing the design and construction of marine vessels, as well as criteria established by reputable classification societies.

Living on the ocean should be at least as safe as travel on the ocean.

11 Conclusions

This report has tried to develop a common understanding on which to base the evaluation of future seastead designs. It is an attempt to integrate all aspects of seastead design into a unified and comprehensive view. It is open to future revision, and will be updated as our collective understanding continues to evolve.

Some general conclusions that can be drawn from the presented analysis are:

- A detailed reading of the legal definition of the continental shelf reveals that shallow waters and international waters are not frequently combined. This implies that mooring and political independence are not easily combined, while both are at least desirable.
- Since this implies a role for station keeping using dynamic positioning, the associated costs have been analyzed in some detail. Large uncertainties still exist, primarily concerning the magnitude of ocean currents at a particular site. However, it can be concluded that station keeping costs may be a primary consideration, since they might end up being prohibitive for some concepts.
- Concepts without rotational symmetry can only benefit from mooring if waves are highly unidirectional. However, we can state with confidence that these elongated shapes also have sufficiently low drag for DP to have bearable operating costs.
- Comfort is strongly dependent on size. Based on considerations of first principles, we can draw the following conclusions:
    - Given conditions in international waters, and excluding migration, only submarines are capable of reconciling comfort with arbitrary small scale. However, the idea of spending extended periods of time beneath the surface of the sea may not be attractive to many potential seastead inhabitants. It is not obvious how to achieve the best of both worlds.

  - Spars need be large along only one dimension in order to function, making them the next smallest concept likely to meet comfort criteria. Due to the unfavorable ratio of topside tonnage to displacement, spars are the least likely of all concepts to be able to implement economical active position keeping

  - Semi-subs need considerable extent in all three dimensions, leading to a large minimum scale. Comfort should be acceptable. A comfort comparison with ships is impossible to make on first principles; given the lower costs of ships, it is not clear how the two compare on a per-dollar basis.

  - Ships are the only concept for which it is obvious that station keeping costs will not be a concern, and for which a considerable degree of migratory flexibility is expected. They can be employed everywhere, granted that their size is sufficient to ensure comfort for a given location.

- Modularity is not the most obvious requirement, but achieving a reasonable and reliable degree thereof is both necessary and non-trivial. It conflicts with anchoring in deep waters, and imposes strict requirements on position keeping abilities. In general, modularity favors large scale seasteads over small scale, as inter-seastead mobility will be less frequently required on a bigger seastead, raising the tolerable cost for such, while at the same time allowing associated equipment costs to be amortized over a larger budget. Larger scale structures are also generally more stable in waves, which further facilitates modularity.