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EARTHQUAKE EFFECTS ON NUCLEAR SAFETY-RELATED LARGE FLOATING STRUCTURES

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ABSTRACT

Large floating structures are of interest in several fields including nuclear power generation, defence, oil and gas extraction and transportation. In each area safety is a key concern, but none more so than in nuclear safety-related structures.

The design of large floating structures must take into consideration several sources of dynamic loading, such as wind, water currents and any associated fluid-structure interaction effects. However, little attention may be given to seismic effects due to limited guidance in relevant engineering codes and standards. During earthquake events, the vertical seismic demand can be amplified at the level of the floating structure thereby introducing a risk with potentially detrimental effects.

There is growing evidence that subsea earthquake ground motions amplify the characteristics of the fluid medium, resulting in an increased dynamic loading on the structure. Even in shallow water depths, the water column directly beneath the structure can amplify the vertical component of the earthquake significantly. In slightly deeper water, cavitation becomes an additional issue due to pressures from incident and reflecting waves.

This paper presents an overview of the issues associated with seismically induced loading on large floating structures, illustrated with examples and followed by recommendations for seismic analysis.

INTRODUCTION

Current standards recognise the need for consideration of additional loading due to undersea earthquakes but provide no guidance as how to calculate and apply these loads. There is growing concern that undersea earthquakes, or seaquakes, can cause dynamic amplification along the vertical axis of the floating structure. In the consideration of the design of safety critical structures, this dynamic amplification can have serious implications.

ASCE 4-98 has been a nuclear industry standard for over 20 years in the UK and internationally. It provides minimum requirements and acceptable methods for the seismic analysis of nuclear safety-related Structures, Systems and Components (SSCs). The scope of ASCE 4-98 covers all safety-related structures of nuclear facilities including buried structures. However, the design of floating structures is outwith its scope.

ACI 357.2R-10 'Report on Floating and Float-in Concrete Structures' states that when evaluating loads for floating structures several sources of load must be considered. Wave loading is the principal consideration but current, wind and tidal loads are also considered. Some site-specific structures, such as floating nuclear power plants or generating stations, also require to be designed for unique vertical pressures and accelerations caused by undersea earthquakes.

This paper presents a brief review of the risk of earthquake effects on large floating structures followed by a practical calculation procedure to determine the order of magnitude of the dynamic amplification during a subsea seismic event. Examples are presented considering different seismic ground motions and different magnitudes of water depth.

LARGE FLOATING STRUCTURES

The interest in large floating structures has increased in recent times in many sectors. Large floating structures, sometimes termed Very Large Floating Structures (VLFSs), can be used to support safety-related facilities and functions, as well as airports, bridges and piers and entertainment facilities. VLFSs fall into two categories: pontoon type and semi-submersible type. Pontoon types simply float on the water surface and are very flexible structures; elastic deformations are more important than rigid body motions and therefore hydroelastic analysis is critical in the design. Semi-submersible types are a simple box structure that is anchored by column tubes, piles or other bracing systems. In the open sea where large wave heights are commonplace, semi-submersible VLFSs can be used to minimise the effects of waves whilst maintaining a constant buoyancy force.

There are many examples of the use of large floating structures. In the 1960s, MH-1A, the first floating nuclear power station, was commissioned for the U.S. Army, NH-1A (2015). The designation MH stood for 'Mobile, High power'. The MH-1A contained a single-loop pressurised water reactor (PWR) in a 350ton containment vessel and used enriched uranium as fuel. The floating power station reached its first criticality in 1967. It was subsequently towed to the Panama Canal Zone where it supplied 10MW of electricity from October 1968 to 1975.

More recently, in Scotland, UK, a covered floating dry dock for handling of explosives for the Trident submarines was built at Hunterston in Ayrshire and floated to the Royal Naval Armaments Depot (RNAD) Base at Coulport, Argyll, Scotland, where it has been situated since 1993, RNAD Coulport (2015). This is one of the world's largest floating concrete structures.

Another example is the Valiant Floating Jetty, a 200m long by 28m wide, 10.8m deep, 42,000tonne floating jetty with a design life of 50 years constructed at Greenock and floated to the HM Naval Base Clyde on the west coast of Scotland. The floating jetty, which cost approximately £130million to build, provides six berths and support facilities for the UK nuclear submarine fleet, NCE (2009).

The Ministry for Atomic Energy of the Russian Federation and Rosatom State Atomic Energy Corporation in Russia projected to mass-build a number of floating nuclear power stations at shipbuilding facilities and then tow them to a suitable location. Construction of the first floating nuclear power station of the Rosatom programme started in 2007 at the Sevmash submarine-building facilities and was later transferred to the Baltic Shipyard in Saint Petersburg. The floating nuclear power station powers two naval propulsion reactors with a capacity of 70MW but other higher capacity reactors may also be used, Russian floating nuclear power station (2015).

There are also non-nuclear related examples. In Singapore, where land space is at a premium, the Float at Marina Bay provides a floating platform 120m by 83m which can be used for sporting events, music concerts, and exhibitions. Space Exploration Technologies (SpaceX) is currently attempting the use of a 50m by 90m floating platform to act as a landing area for reusable orbital launch vehicles. Shell is also constructing a floating platform to house a liquefied natural gas (LNG) plant.

EARTHQUAKE EFFECTS ON FLOATING STRUCTURES

Only a few authors have examined seaquakes and their effects on structures. Williamson et al. (1975) examined the dynamic response of submarine ships subject to an underwater explosion. The analysis showed that the shock wave transmitted from the seabed to the ship is amplified by approximately 16 to 20 times depending on the water depth. However, no experimental validation was conducted to verify these computational results.

Okamoto and Sakura (1993) argued that seaquakes are caused by the propagation of the vibration of the seabed through seawater. The source of the vibration is an earthquake under the seabed. However, an underwater explosion can also cause much the same effect, causing propagation of energy through a fluid medium vertically.

Thangam Babu and Reddy (1986) stated that the shockwaves induced by the sea during seismic events consist only of acoustic waves as water cannot transmit shear waves. Seismic vibrations transmitted through the water from the seabed to a floating structure cause a high-frequency response, with the excitation consisting of vertical pulses inducing compression and tension waves in the water. Cavitation results when the tensile stress exceeds the compressive stress due to the atmospheric pressure plus the weight of the water above.

Thangam Babu and Reddy employed the finite element method (FEM) to formulate the non-symmetric coupled dynamic equations of equilibrium of the fluid-structure continuum. A linear system of lumped masses, springs and dashpots is used to study the amplification of the earthquake through the fluid medium. The number of finite elements is limited for the computation speed and accuracy desired. Moreover, the infinite nature of the fluid medium had to be limited and was achieved by defining a boundary at which the response (the added mass and damping) did not change by more than 1%. The results showed that the fluid medium amplifies the vertical acceleration considerably, therefore discrediting the claim that floating power plants would be unaffected by earthquakes.

Baba (1987) and Matsuoka (1988) performed studies on the effects of seaquakes on marine structures using the potential theory of incompressible fluids. The study examined a flat seabed in open water vibrating vertically and concluded that a floating structure makes the same movements as the seabed.

A PRACTICAL APPROACH FOR STRUCTURAL ANALYSIS

A simple and practical method employing a model which consists of a linear spring with a nodal mass will be used here to establish the dynamic amplification resulting on a large floating structure by a subsea earthquake. The water column is assumed to act as an elastic spring with the vertical sides restrained from horizontal displacement. The nodal mass at the tip of the spring represents the structural load whilst the load of the water column is attached to the spring, see Figure 1. Two different response spectra, a Principia Mechanica Limited (PML) response spectrum, and a response spectrum representing the Taft earthquake ground motion, will be considered for different depths of water. To gauge the influence of the mass of the water column, it will be ignored initially but will be included in a second iteration of analysis.

Consider an object that is plunged vertically into a liquid by the distance η_3, Blevins (1986). The buoyancy force applied hydrostatically to the object will increase by the weight of the displaced liquid, $\rho g \eta_3 S$, where ρ is the density of the liquid, g is gravitational acceleration and S is the area enclosed by the waterline of the object. Therefore, a heaving motion (vertical translation perpendicular to the free surface of the liquid) can be analysed by modelling the hydrostatic buoyancy force as a spring constant, see Equation 1. The spring stiffness is represented by k, with E the Young's modulus, A the area and L the spacing of the masses. The natural frequency, *f*, of the heaving motion is then found from the equivalent spring-mass system, Equation 2, where *M* is the mass of the system.

$$k = \frac{EA}{L} \tag{1}$$

$$f = \frac{1}{2\pi}\left(\frac{k}{M}\right)^{1/2} \tag{2}$$

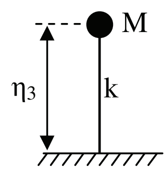

Figure 1: Computational Model

A 20m by 20m in plan by 2m deep structure with a mass of 2,000t is assumed. A PML soft site response spectrum for a peak ground acceleration (PGA) of 0.25g and 5% damping is selected as a generic example for illustration purposes. The choice of ground motion data for a real life problem should take into consideration site specific conditions. ASCE 4-98 recommends using 2/3 of the values of the horizontal motion, as shown in Figure 2. The stiffness can be calculated from Thangam Babu and Reddy (1986), given in Equation 1, where E = 132MN/m^2. In the cases to be examined, the spring is not subdivided and so the water mass is lumped equally to both nodes and therefore *L* is simply the length of the spring.

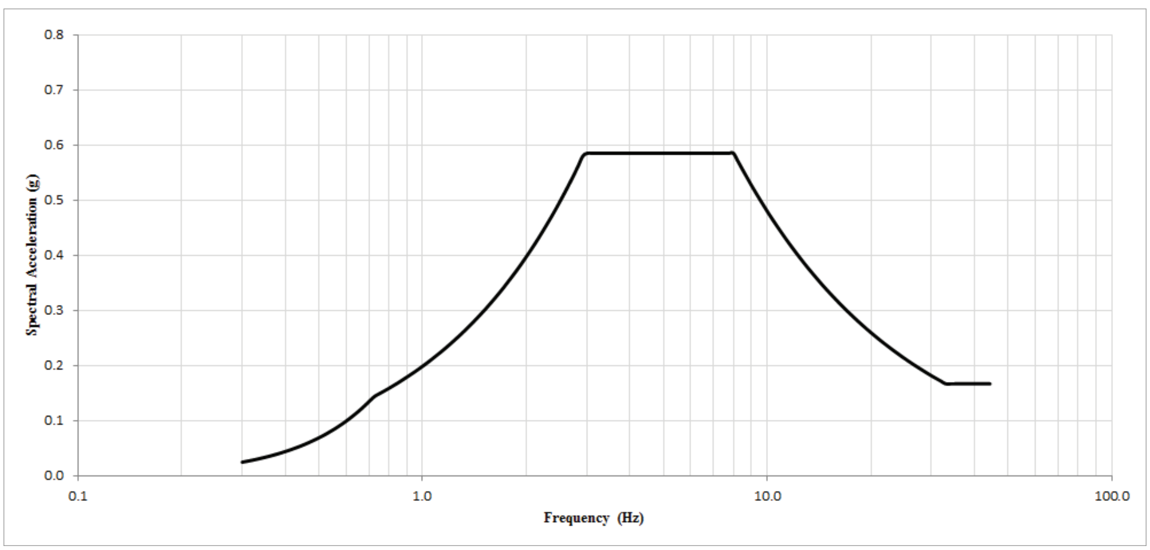

Figure 2: PML Response Spectrum

The representative spring stiffness can be calculated from Equation 1, and the fundamental frequency can be calculated from Equation 2. Hence, from Figure 2 the spectral acceleration ***a*** is found. Thus the seismic force can be calculated from Equation 3, where *g* is gravitational acceleration and *M* is structural mass.

$$F_{seismic} = agM \tag{3}$$

Different depths of water are now considered starting at 1m up to 100m. Two conditions are examined for each depth of water; one ignoring the mass of the water column, and the other including the mass of the water column. Likewise, both an undamped and damped response is examined for each analysis with 0.5% damping assumed for the water column. The reaction at the base of the spring is derived in SAP2000 and the indicative seismic amplification factor is calculated from the sum of the base reaction and the hydrostatic force divided by the hydrostatic force. Figure 3 depicts the resultant seismic amplification factor versus water depth.

The figure shows that even at shallow water depths the force on the structure is amplified by a seismic event. In the cases where the mass of the water column is ignored, the amplification factor plateaus between 10m and 70m because the fundamental frequency of the structure is within the peak range of spectral acceleration. In the cases that include the mass of the water column, the amplification factor peaks at 30m, and demonstrates an increase of up to ten to sixteen times the hydrostatic force depending on the undamped or damped response. Moreover, the amplification factor does not drastically reduce as the water depth increases. At only 1m water depth the force on the structure is doubled. Therefore, it is clear that during a seismic event, the hydrostatic force on the structure is amplified, with the magnitude of the amplification dependent on the depth of the water.

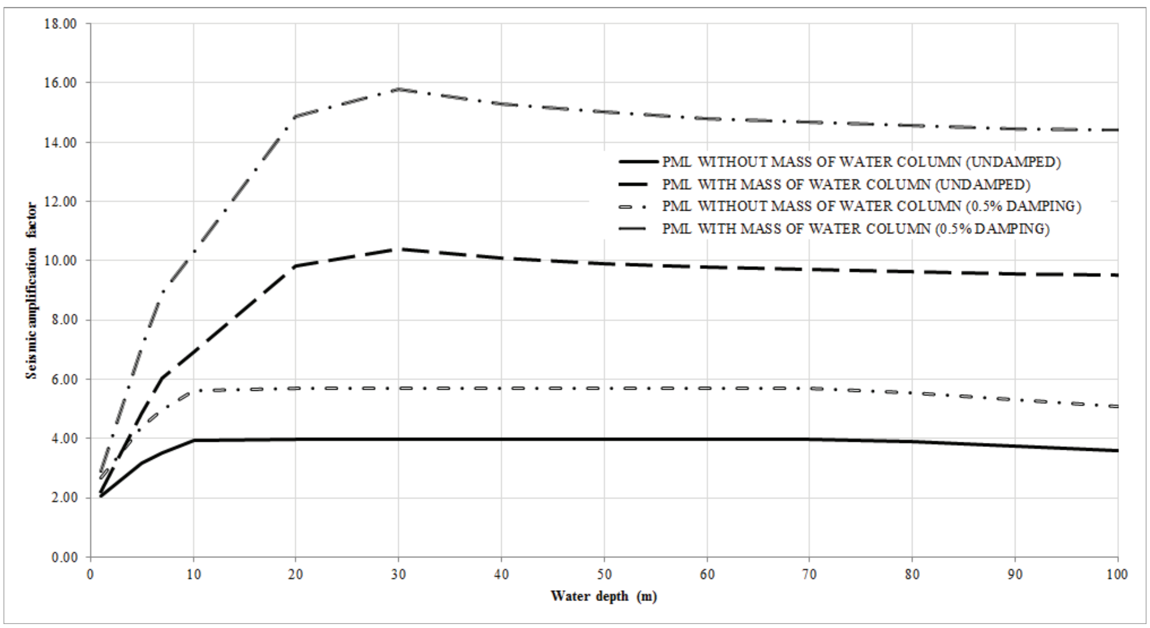

Figure 3: Seismic amplification factor versus water depth for PML Response Spectrum

During the 1952 Arvin/Tehachapi earthquake in California, ground accelerations were recorded at Taft, California on an instrument maintained by the US Coast and Geodetic Survey. Housner (1953) derived a response spectrum from the accelerograms, as shown in Figure 4.

The same example is now subjected to this motion. Figure 5 depicts the resultant seismic amplification factor versus water depth for analyses considering and not considering the mass of the water column. It can be seen that the response which considers the mass of the water column indicates a maximum amplification of the hydrostatic force of approximately thirty five times during a Taft-equivalent seismic event at a water depth of 30m. Even at low water depths, the hydrostatic force is amplified by a factor of approximately five. The results appear to indicate what has been previously reported by Thangam Babu and Reddy (1986) is correct; the amplification factor for a Taft ground motion was approximately 30 for a water depth of 40feet.

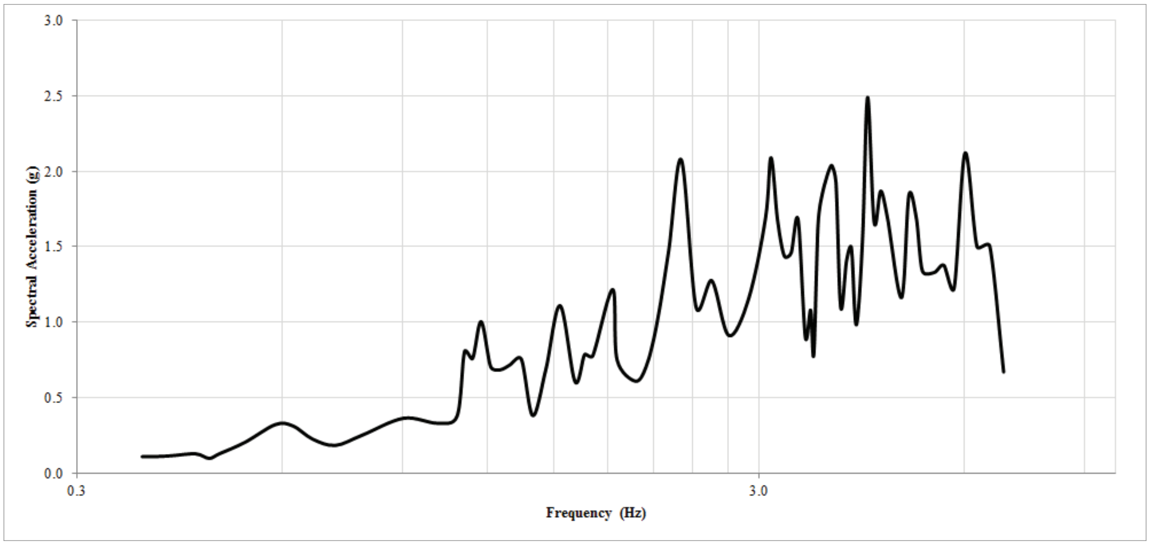

Figure 4: Response spectrum generated from the Taft Accelerograms (no critical damping)

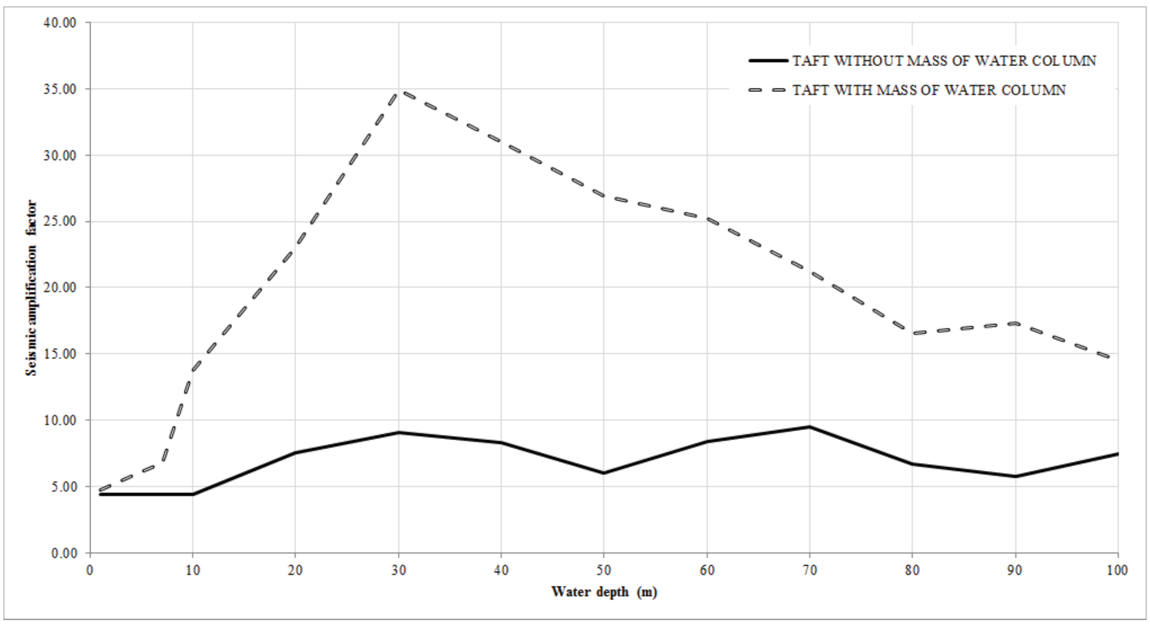

Figure 5: Seismic amplification factor versus water depth for Taft Response Spectrum

CONCLUSIONS

A simple and practical approach has been presented that demonstrates that a seismic event can magnify significantly the vertical hydrostatic effects on a structure. For a series of analyses considering the Taft earthquake motion, the hydrostatic force was amplified in the range of five to thirty five times, depending on the water depth. For a series of analyses considering the UK PML spectra the hydrostatic force was amplified in the range of two to sixteen times approximately. Whilst all combinations of seismic events and floating systems are dissimilar, it is clear that there can be a significant risk imposed by subsea earthquakes on large floating structures which should be considered in the design.

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