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EXPECTED PEAK RESPONSE (EPR) ANALYSIS OF THE EFFECT OF HYDRODYNAMIC INTERACTION ON THE SUBMERGED MARINE TUNNELS, CASE STUDY: POHL-LAFT CORRIDOR ON QESHM ISLAND

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ABSTRACT
The advantages of submerged marine tunnels were first discussed. Then, the appropriate numerical methods for dynamic analysis and prediction of wave effects on submerged marine tunnels were explained with regard to environmental conditions. The dynamic effects of wave loading on the submerged marine tunnel with long thin shell structure were simulated by Fedaf. The time-domain and frequency-domain structural analyses were performed using MATLAB. The degrees of freedom (DOFs), stiffness matrix and other structural and hydrodynamical parameters were also determined. As a case study, the Pohl-Laft tunnel (Pohl Port of Bandar Abbas and Laft Port on Qeshm Island) was studied due to its similarity to Hags Jared highway in Norway. Finally, expected peak responses (EPR) and displacements in different directions were calculated for the submerged marine tunnel. Recommendations were offered for the use of this new structure to connect the southern islands in the Persian Gulf to the coastal regions, especially for the bridge linking the Persian Gulf to Qeshm Island.

KEYWORDS: EPR, Fluid-Structure Interaction, Hydro dynamical Analysis, Submerged Marine Tunnel.

INTRODUCTION

Submerged marine tunnel is a new concept in underwater communication and is one of the new types of marine structures. The design technology and the preconstruction of submerged tunnels are studied in some developed countries in terms of feasibility studies and national projects. This type of marine structures has not been built in real scale, but can be placed against the surface floating bridges. In Norway, Hags Jared highway is proposed to be constructed between Louvain and Ana's by a marine submerged tunnel with a span length of 1400 m as the first structure of this type in the world. It is predicted that 2500 vehicles per day will pass one of the main roads in the south west Norway. Hags Jared Highway and Pohl-Left Corridor are seen as pilot projects to raise the computational and commissioning skills for this type of straight waterways with long shell structure. One of the most important computational problems for such structures is overall dynamic analysis and fluid-structure interactions (FIS). The present study mainly focuses on these issues. The feasibility studies on construction of submerged marine tunnels have increased in the last two decades given the scientific research facilities and capabilities. Previous studies have mainly focused on the surface floating bridges. For example, Sal house Bridge in Norway (better known to Noterland-Bra) is an example of surface floating structures. The idea of submerged submarine tunnels is quite similar to the reactions of the marine environment on the structure. But there is a different set of parameters which should be recognized. Since the idea of submerged tunnels (have not yet made) was introduced, loading estimates showed that certain conditions must be considered for the both Hags Jared project and Bandar Abbas- Qeshm Corridor.

OTHER IDEAS AND CONCEPTS OF SUBMERGED MARINE TUNNELS

So far, the supports of this type of structures (pantone, tension leg other types) are not well defined. Moreover, the general shape and geometrical details (longitudinal and transverse), either straight or curved paths, are not determined. The best option for the Persian Gulf waterway is Norwegian contractor's proposal where the main body is made of concrete or glass fibers with tension legs anchored to the seabed as shown in Figure 1. The other proposals are as follows: 1. The Selmer Furuholman: the main body is made of concrete with pantones connected to the concrete body (Figure 2), 2. Cavarner Rosenberg: the main body is made from steel with pantones connected to the metal truss as shown in Figure 3, 3. Henriksen Inc: the main body is made of concrete with pantones connected to the metal truss (Figure 4).

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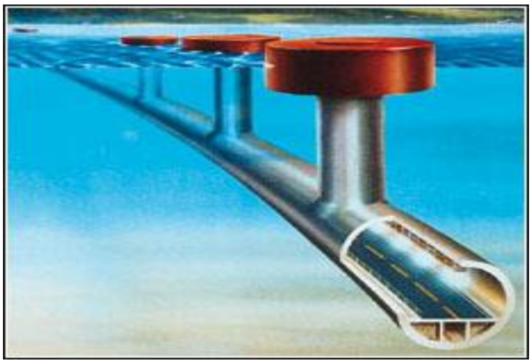

Fig.2. Selmer Furuholman

Fig.1.Norwegian contractor's proposal

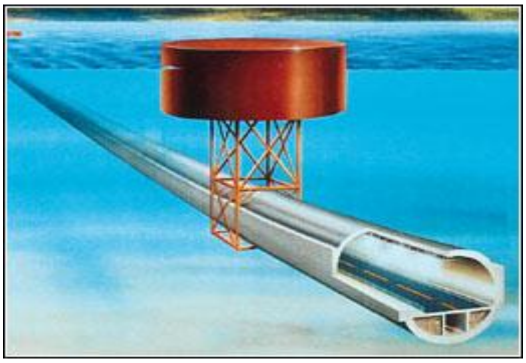

Fig.3. Cavarner Rosenberg

Fig.4.Henriksen Inc

Types of supports

The support for this type of structures should be selected based on the parameters affecting its dynamic behavior. It is of great importance so that it should be on top of other issues regarding the submerged marine tunnels. In this regard, a variety of cross-sectional models and longitudinal arches as well as support conditions should be investigated. According to above figures, the proposals can be categorized into two different ideas based on the type of supports along the bridge span. Both pantones and tension legs can be used for this purpose. In this study, the free span bridges were studied to include the effects of dynamic loading of irregular waves. The effect of the curvature of the bridge was also analyzed.

Loadings and their effects on submerged marine tunnels

- Traffic loads
- Structural weight and immersion forces
- Flows
- Waves
- Loads caused by internal waves
- Wind load
- The load caused by ships and large ice pieces
- Earthquake load
- The effects of pre-stressed concrete, temperature, creep, shrinkage and support settlement

Among the dynamic loads, the dynamic effects of wave loading are more important to analyze the dynamics of submerged marine tunnels and flow-structure interactions.

Wave loading on submerged marine tunnels and flow-structure interaction

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The dynamic analysis of submerged marine structures is performed based on the loading type and the behavior of responses induced by wave loading which shows both the actual effects on the structure and loading effects. Accordingly, the response of the system known as "flow-structure interaction (FSI)" is obtained by combining structural modeling and hydro dynamical models. The separate boundary layers at the outermost surface of the tunnel and marine algae settling at different cross sectional levels may cause loads per unit length of the tunnel. In general, the design of tunnel based on pantones or tension legs will be affected by the structural frequency function.
The difference between the computational fluid dynamics (CFD) and fluid-structure interaction (FSI) should be considered in these shell long structures. If the tunnel is shorter (up to several times the outer diameter), FD should be included in constant boundary conditions.

Governing equations
The equations governing fluid-structure interaction (FSI) under wave loading on submerged marine tunnels are derived based on the dynamic response of the structure. Both time-domain and frequency-domain problems are solved using the principle of superposition. Then, the calculations are manually controlled. Finally, the various methods are compared and analyzed through an illustrative example.

Fluid-structure interaction (FSI) modeling
Geometrical model of the structure
Many arbitrary geometrical models can be provided in terms of the structural requirements. The following items should be considered for this purpose [Bergan *et al.*, 1986]:

- Balance
- Material properties
- Deformation consistency

Considering the above items, the differential equations are satisfied and the problem is solved.
Equation (1) includes the following three basic parts:
[1] $$M\cdot\ddot{u}+C\cdot\dot{u}+K\cdot u = P\,(t)$$
The most important point in FSI problems is that flow force is not only dependent on the loading parameter P (t), but will change by the mass, damping and stiffness of the structure.
As a result, the dynamic behavior of the structure should be a combination of several vibrational modes. But it is recommended to use the first two critical vibrational modes. "The dynamic magnification factor of the structural system" known as "mechanical transfer function H (ω)" containing information on the previous paragraphs is a frequency-domain function and shows the maximum natural frequency of the structure. Hence, it shows all loads applied to the structure with output frequencies leading to spectral solutions larger than the loading among output frequencies [Chakrabarti, 1987].

Hydro dynamical model
Sea waves represent the fluid in fluid-structure interaction problems. In this section, the governing equations and basic assumptions are discussed. Figure 5 shows the linear wave theory and boundary conditions [Dean, 2000].

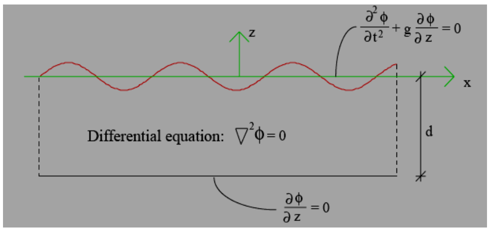

Fig.5. The linear boundary conditions applied to flow

Such problems with above boundary conditions and the potential function ϕ are differentiable for any parameter such as pressure, level, height, velocity, etc. Equation 2 at the fluid surface is written as follows:
[2] $$\eta = a\cdot\sin(\omega t - kx)$$

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- Structural aspects may be much larger than the area where wave refraction occurs.
- Diffraction may occur for marginal and small structural elements.

The structure of the submerged marine tunnels is exposed to very large longitudinal waves. Hence, a circular main body is proposed for the structure. As a result, the diffraction of singular waves is unlikely to occur regardless of the flow effects. As a practical design, the spectral density function is used to determine the frequency in real conditions. The spectral density function proposed for the submerged marine tunnel is written according to Jonswap spectrum as follows:

$$S_{\eta}(\omega) = \frac{\alpha . g^2}{\omega^5} . e^{-\frac{5}{4}\left(\frac{\omega}{\omega_0}\right)^{-4}} . \gamma^{\left(e^{-\left(\frac{(\omega-\omega_0)^2}{2\sigma^2 . \omega_0^2}\right)}\right)} \quad [3]$$

where ω_ρ indicates the maximum spectral density function and s denotes sharpness (s= 0.07 for $\omega < \omega_\rho$ and 0.09 for other values). □□ is used for adjusting the spectral density and the wave height, H_s. Therefore, the spectral density includes the maximum frequency and characteristic height of waves. Figure 6 shows the density function of swap for calm sea conditions with ω_ρ=1.26 rad/s, wave period of 5.5 s and H_s=0.2 m.

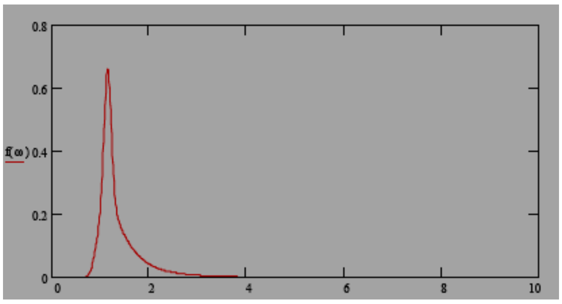

Fig.6. Jonswap density function

Numerical models

The overall geometry of the structure

Here, three tunnels with different geometries are studied [Paik *et al*., 2008] [Bergan *et al*., 1986]. In all cases, the span is 1500 meters. The distance between Pohl and Laft ports is1400 m. A distance of 1500 m is considered with regard to the tunnel connection to the drought sides and possible excavations.

1. Free-span straight tunnel is the best and most convenient option to compare different analysis methods and demonstrate the dynamic effects of the flow-structure interaction caused by irregular waves on the structure of submerged marine tunnels. By analyzing this simple case, the effects of curvature and support constraints (such as pantones or tension legs) along the tunnel are studied separately.
2. Free-span arc tunnel is constructed to compare with the straight path.
3. Arc tunnel with several support constraints along the tunnel is used to show the effects of tension legs (tendons) at certain points along the tunnel. This is also used to illustrate the effects of support constraints in different places along the tunnel. This allows the prediction of the effects of pantones. The geometry of the arch tunnel is shown in Figure 7:

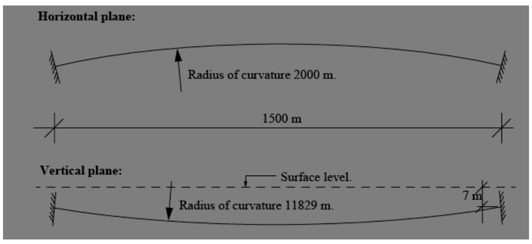

Fig.7. The overall geometry of tunnel

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For the straight tunneling, the overall structural depth of 15 m above the sea level from the center of the circular body of the tunnel is obtained. The distance between all tension legs is assumed to be 300 m. For all cases, 50 elements along the tunnel were selected. Figure 8 illustrates a particular node. The analysis in subsequent chapters is based on these nodes.

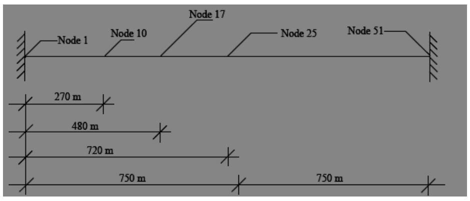

Fig.8. Nodes 10, 17 and 25 in the submerged tunnel

Materials properties and cross sectional characteristics

The main body of the tunnel is made of concrete with a circular cross section. Table 1 summarizes the mechanical properties.

Table1. The mechanical properties of the tunnel

Young Modulus of the main body	$3.5 * 10^{10} \frac{N}{m^2}$
Poisson ratio of the main body	0.2
Outer diameter of the main body	11.6 m
Inner diameter of the main body	9.6 m
Moment of inertia of the circular cross section	471.9 m4
Polar moment of inertia of the cross section	943.7 m4
Cross sectional area	33.3 m2

The spring stiffness of the tension legs should be modeled simultaneously with the structural modeling. The tensile elongation of the legs will be 10% of the buoyancy forces at edges. Since the distance between the tension legs is 300 m, approximately 10% of the weight of the submerged cross section should be multiplied by 300 m and the density of water (Figure 9).

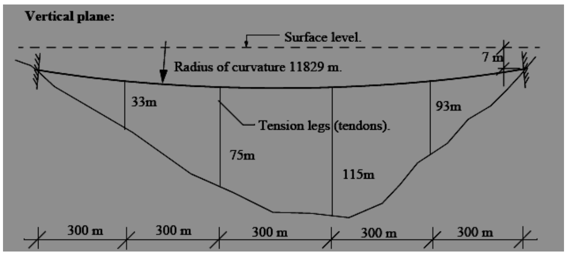

Fig. 9. Tension legs in the arch tunnel

Modal analysis

Knowing the basic dynamics of the structure, the natural vibrational modes play an important role in determining the behavior of structures subjected to dynamic loads. Tables 3 to 5 show the characteristic values for the three models.

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Table 2: Natural vibrational modes for the free-span straight tunnel

Eigenvalue number	Circular freq. (rad/sec.)	Frequency (Hz)	Period (sec.)	Dominant Displacement direction
1	0.0849	0.0135	74.0000	**Heave/sway**
2	0.0849	0.0135	74.0000	**Heave/sway**
3	0.2340	0.0372	26.8600	**Heave/sway**
4	0.2340	0.0372	26.8600	**Heave/sway**
5	0.4587	0.0730	13.7000	**Heave/sway**
6	0.4587	0.0730	13.7000	**Heave/sway**
7	0.7582	0.1207	8.2870	**Heave**
8	0.7582	0.1207	8.2870	**sway**
9	1.1330	0.1803	5.5470	**Heave/sway**
10	1.1330	0.1803	5.5470	**Heave/sway**
11	1.5820	0.2518	3.9720	**Heave**
12	1.5820	0.2518	3.9720	**sway**
13	2.1060	0.3352	2.9830	**sway**
14	2.1060	0.3352	2.9830	**Heave**

Table 3. Natural vibration modes for the free-span arc tunnel

Eigenvalue number	Circular freq. (rad/sec.)	Frequency (Hz)	Period (sec.)	Dominant Displacement direction
1	0.0814	0.0130	77.2300	**Heave**
2	0.2254	0.0359	27.8800	**sway**
3	0.2264	0.0360	27.7500	**Heave**
4	0.4035	0.0642	15.5700	**sway**
5	0.4449	0.0708	14.1200	**Heave**
6	0.7344	0.1169	8.5560	**sway**
7	0.7355	0.1171	8.5430	**Heave**
8	0.9708	0.1545	6.4720	**sway**
9	1.0980	0.1748	5.7220	**Heave**
10	1.2270	0.1952	5.1230	**sway**
11	1.5320	0.2437	4.1030	**sway**
12	1.5330	0.2439	4.1000	**Heave**
13	2.0390	0.3246	3.0810	**Heave**
14	2.0520	0.3266	3.0620	**sway**

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Table 4. Natural vibration modes for the arc tunnel with tension legs

Eigenvalue number	Circular freq. (rad/sec.)	Frequency (Hz)	Period (sec.)	Dominant Displacement direction
1	0.2490	0.0396	25.2300	**sway**
2	0.4229	0.0763	14.8600	**sway**
3	0.7601	0.1210	8.2660	**sway**
4	0.9897	0.1575	6.3480	**sway**
5	1.0640	0.1693	5.9080	**Heave**
6	1.2500	0.1990	5.0260	**sway**
7	1.2820	0.2040	4.9030	**Heave**
8	1.5720	0.2501	3.9980	**sway**
9	1.5790	0.2512	3.9800	**Heave**
10	1.8430	0.2933	3.4100	**Heave**
11	2.0290	0.3229	3.0970	**Heave**
12	2.1060	0.3352	2.9830	**sway**
13	2.6850	0.4237	2.3410	**sway**
14	3.3560	0.3542	1.8720	**sway**

Frequency-domain analysis

In this paper, the software is used to analyze the direct frequency response. This software is known as Fedaf and was developed by Sean Tef [Leira, 1988] [Leira *et al.*, 1988] in Norway's Ministry of Transportation, Department of Structural Engineering. The computational procedure is as follows:

Structural model and calculation of M, C, K	→	The hydrodynamic transfer function F(ω) is obtained using the frequencies determined in the first section.

The computational procedure of Fedaf

The numerical calculations

The most important parameter in the basic design is the expected peak response (EPR) which is obtained from the spectral density function based on the standard deviation (SDV). SDV is calculated using the square root of the integral of the spectral density function. It is noteworthy that EPR should be calculated based on the calm steady state sea conditions and the continuation of the specified time period. The relationship between EPR and SDV is as follows:

$$EPR = SDV \cdot \left\{ \sqrt{2.\ln\left(\frac{\Delta T}{T_z}\right)} + \frac{0.5772}{\sqrt{2.\ln\left(\frac{\Delta T}{T_z}\right)}} \right\}$$

Where ΔT should be calculated in calm sea conditions and Tz is the period over the zero point of the Jon swap function where Tp = 1.2 Tz. In this study, a time period of 300 s with short continuation is used. The analysis was carried out only for comparison with the results in the next season. Since TP = 5.5 s, the relationship between EPR and SDV will be as follows:

$$EPR \approx 3 \cdot SDV$$

Numerical calculations for free-span straight tunnel

Due to the irregular sea waves, the spectral density function used in this study is Jon swaps function (Figure 10), in which H_s= 2.03 m T_p=5.5 s.

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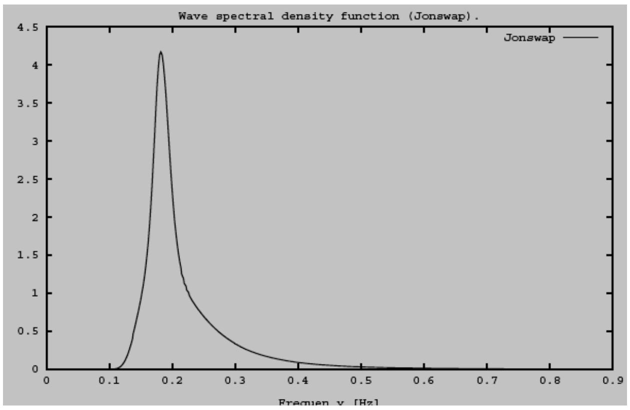

Fig.10. Wave spectral density function (Jonswap)

Figures 11 to 14 show EPR changes for displacements along sway, heave, yaw and pitch directions.

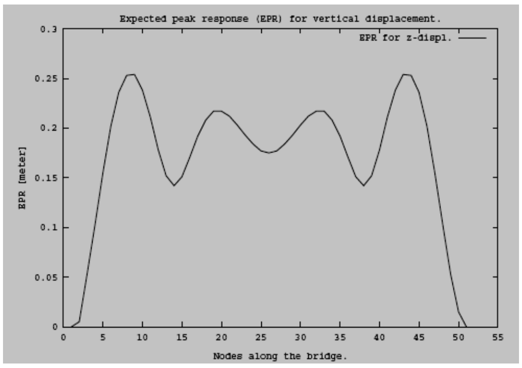

Fig.12. EPR along heave direction

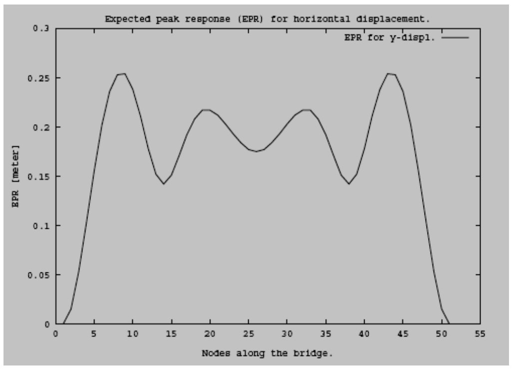

Figure. 11. EPR along sway direction

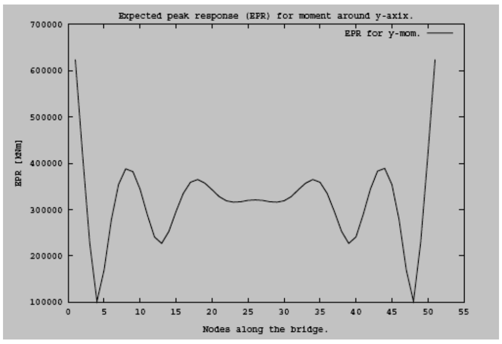

Figure 14: EPR along pitch direction

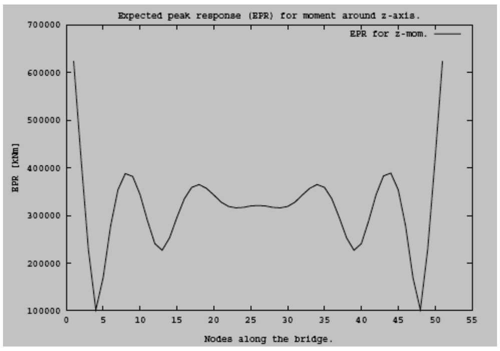

Figure 13: EPR along yaw direction

Numerical calculation for free-span arch tunnel

Figures 15 to 18 show EPR changes for displacements along sway, heave, yaw and pitch directions.

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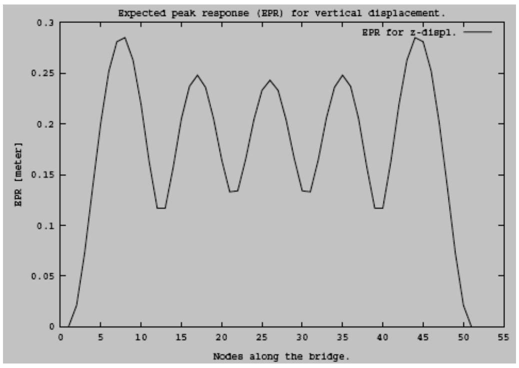

Fig.16. EPR along heave direction

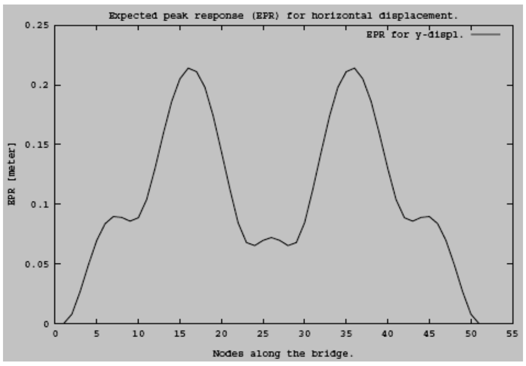

Fig. 15. EPR along sway direction

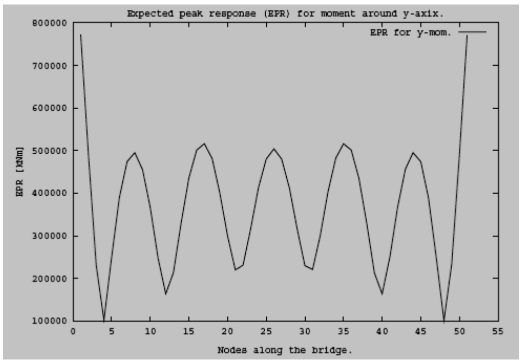

Fig. 18. EPR along pitch direction

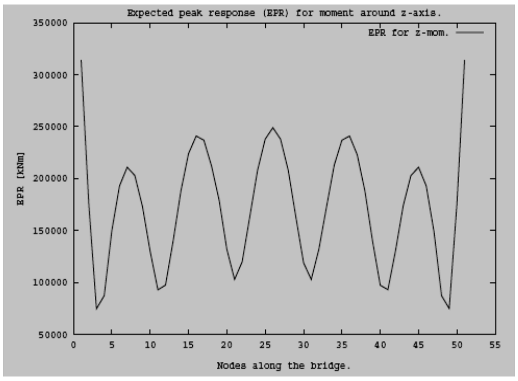

Fig. 17: EPR along yaw direction

Numerical calculations for arc tunnel with tension legs

Figures 19 to 22 shows EPR changes for displacements along sway, heave, yaw and pitch directions.

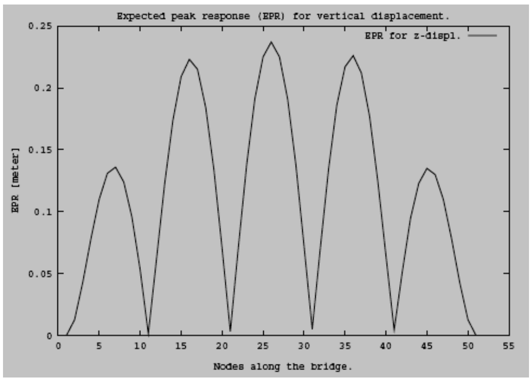

Fig. 20: EPR along heave direction

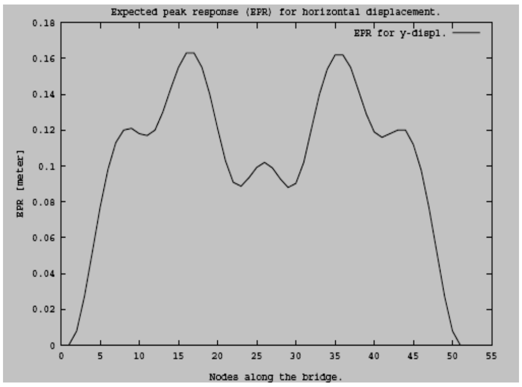

Fig. 19: EPR along sway direction

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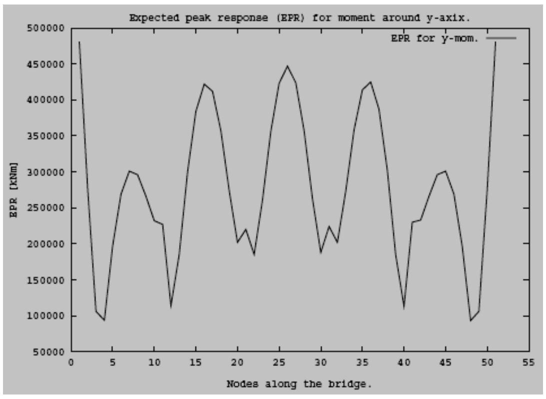

Fig. 22: EPR along pitch direction

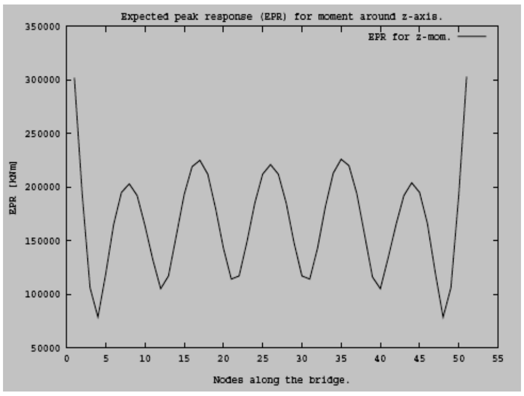

Fig. 17: EPR along yaw direction

CONCLUSION

The advantages of submerged marine tunnels were first discussed. Then, the appropriate numerical methods for dynamic analysis and prediction of wave effects on submerged marine tunnels were explained with regard to environmental conditions. EPR results showed that the calculations based on calm sea conditions should be compared with the results obtained from time-domain calculations. The EPR results should be multiplied by 4.3 for normal sea conditions (about 2 h). The motion along heave and sway directions shows almost a same behavior for the free-span straight tunnel. Moreover, the displacement and momentum are the same in both directions. For the free-span arc tunnel, the overall momentum along the tunnel is of great importance. Yaw moment is reduced because the lower natural mode (fewer waves along the tunnel) is dominant to displacement along sway direction. Accordingly, the pitch moment increases until the heave displacement is dominant at higher vibrational modes. The arc tunnel with tension legs showed a quite similar behavior. In this case, the motion is of sway type. However, sway motion decreases since the stiffness of the spring acts as tension legs.

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