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Investigation of the effect of modulus of elasticity on seismic performance of quay walls considering interaction effects

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***Abstract*—This paper examines the effect of the modulus of elasticity of the quay wall on its seismic response with respect to interaction effects. Finite Element Method (FEM) was used for analysis purposes and interaction between wall, fluid, and foundation was incorporated in the model. Given the behavior and geometry of quay wall, modeling is conducted in a two-dimensional manner and Newmark method was used for dynamics analysis. Seismic analysis of Antwerp quay wall in Belgium was used as a case study. In order to investigate the effect of modulus of elasticity (E), this model was analyzed in various modes and then results were compared to each other.**

Keywords—Earthquake; modulus of elasticity; quay wall; interaction; time history analysis

I. INTRODUCTION

Given the expansion of maritime trade, increasing number and size of vessels as well as marine transgression and potential of sea level fluctuation, study of seacoast protection is of crucial importance. A structure which is normally used to protect the coast of sea is quay wall. Quay walls are considered as important structures which need to be carefully analyzed and design. Safety and cost-effectiveness are two key factors in design of such structures. One major issue in design of a quay wall is the interaction among quay wall, fluid, and foundation during the earthquake. Interaction of a quay wall with fluid contributes to the increased vibration period of the wall and that is why quay wall is unable to move without displacement of fluid tangent to quay wall. The fluid moving together with quay wall increases the total mass moved by the earthquake. This added mass contributes to the increased vibration period of quay wall and therefore affects the inertia force caused by earthquake. In dynamic analysis, therefore, effects of fluid and related boundary conditions need to be taken into account in dynamic response. Earth movement and displacement of quay wall upstream face creates a hydrodynamic pressure within fluid behind the wall which in turn influences the displacement of quay wall upstream face. Hence, the dynamic behavior of quay wall and fluid are not independent and therefore need to be simultaneously analyzed taking into account the appropriate boundary conditions and interaction issue [1].

Analysis of the hydrodynamic forces on a hydraulic structure was first conducted by Westergaard in 1933 where the hydrodynamic pressure calculated using the added mass [1].In 1967, chopra studied the Fluid compressibility effects on force due to fluid-structure interaction [2]. Zienkiewicz first demonstrated the finite formulation for showing the response of a submerged structure assuming incompressibility of water in 1965 [3]. Finite element formulation is difficult due to unlimited range of fluid. To solve this problem it needs to unlimited range be intersected in a certain distance of structure. In 1978, Zienkiewicz tested the finite element formulation for solving the equation of the fluid infinite-ranged compressive wave [4].Chopra (1970) used the finite element method as a numerical technique for hydraulic structure - fluid analysis. He studied the response of the hydrodynamic force on a hydraulic structure under horizontal excitation [5].Mei et al (1979) published an exact solution for structure-fluid interaction in time scale [6]. Hall and Chopra (1982) studied the hydrodynamic effects of the fluid on the seismic response of hydraulic structure using one-dimensional boundary conditions for the radiation of waves in truncated boundary [7]. Chen (1995) and Lee et al. (1999) conducted studies on effects of earthquakes on marine structures and quay walls. In their studies they failed to exactly incorporate the interaction effects [8, 9].

II. APPLICIABLE EQUATIONS

In this section, structural and hydrodynamic considerations are described. Fluid is considered as non-viscous, uncompressible, with minor displacement and quay wall and foundation are considered as solid and elastic with linear behavior of materials.

A. *Applicable Equations for Fluid Behind the Quay Wall*

In problems related to the acoustic interaction between structure and fluid, equation of structure dynamics need to be considered together with Navier-Stokes equations, momentum and continuity of the fluid. Assuming a non- viscous incompressible fluid with minor displacements, continuity equation and momentum are summarized to wave equation. Furthermore, applied pressure on structure from fluid at the interface is considered to form the interaction matrix.

$$\nabla^2 P = \frac{1}{C^2}\frac{\partial^2 p}{\partial t^2} \quad (1)$$

(Where, $C = \sqrt{\frac{k}{\rho_0}}$ is the acoustic wave velocity in fluid, k is the bulk modulus of fluid and ρ_0 is the specific mass of fluid, P is hydrodynamic pressure, and t is time.

B. Applicable Equation on Quay Wall

In linear dynamic analysis, applicable equation on this system is provided as follows:

$$M\ddot{U} + C\dot{U} + KU = M\ddot{U}_g + F_{pr} \quad (2)$$

Applied load from fluid hydrodynamic pressure at the interface of structure and fluid is added to structure equation in order to take into account the interaction between fluid and structure (in above equation).
In above equation M, C, and K represent mass, damping, and rigidity matrices, respectively. $\ddot{U}$,$\dot{U}$ and U represent acceleration, velocity and displacement matrices applied on the system, respectively. $\ddot{U}g$ is the acceleration due to earthquake and Fpr is the hydrodynamic force applied from the fluid which is created due to the interaction fluid and quay wall interface.

III. Introduction and Analysis of Model

In this analysis, quay wall is considered as concrete type, unreinforced, elastic which is made from materials with homogenous, linear, and isotropic behavior; fluid behind the peripheral quay wall is considered as homogenous, compressible, non-viscous, non-rotational and with minor displacement; soil and sediment is considered as homogenous; effects of surface wave were ignored and pressures at free level of fluid was considered zero.

Given the applicable conditions on the behavior of quay wall, this system is considered as a two-dimensional one. System specifications are summarized as follows:Specific weight and Poisson's ratio of wall concrete is assumed 2400 kg/m3 and 0.2, respectively. For soil, modulus of elasticity (E) is 0.1 Gpa, Poisson's ratio is 0.3, density is 2,000 kg/m3, coefficient of permeability is 9.2e-6 m/s. for water, density is 1000 kg/m3, height is 14m; for sediment, height is 3m and density is 1926 kg/m3. Because the main objective of current paper is to investigate the effect of quay wall modulus of elasticity on its seismic response, intended model was analyzed for five modes. For wall, modulus of elasticity was considered 15, 20, 25, 30.5 and 35 Gpa.Dimensions of quay wall is shown in figure 1 [10];and Model geometry is shown in figure 2.

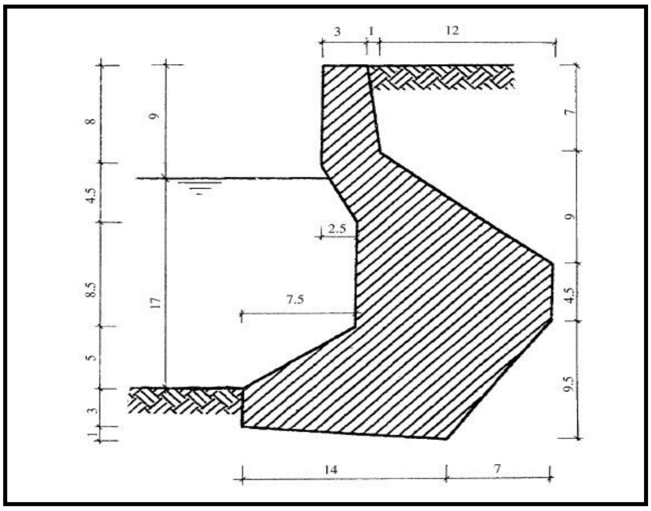

Fig. 1.*Quay wall model*

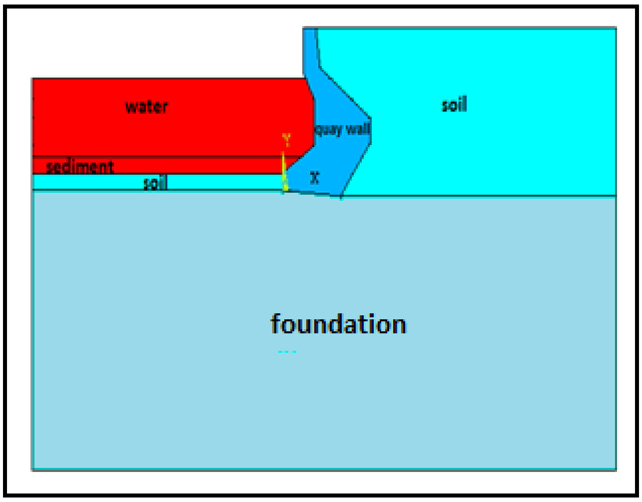

Fig. 2.*Model geometry*

paragraph. DoIn current paperpaper, Finite Element Method (FEM) was used to seismically analyze the quay wall. This software has the feature of seismic analysis taking into account the irregular geometry of ranges and interaction effects of fluid and foundation.El centro accelerogram was selected to dynamically analyze the horizontal and vertical elements. Maximum horizontal acceleration of this earthquake is 0.35g.Newmark method was used for numerical integration where its parameters were chosen as$\beta = 0.25$ and $\gamma = 0.5$, and time step was set at$\Delta t = 0.02$. Furthermore, appropriate absorbing boundaries were intersected at distant boundary and were defined at the bottom of fluid and Sommerfeld boundary condition was used for distant intersected boundary. For dynamic analysis, Antwerp quay wall in Belgium with height of 30 was regarded as a case study [10].Figures 3 and 4 show the seismic El centro accelerograms occurred in 1940.

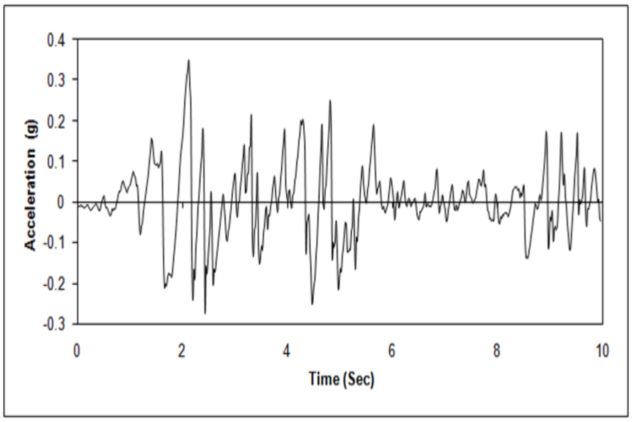

Fig. 3. *North-south element of El centro earthquake*

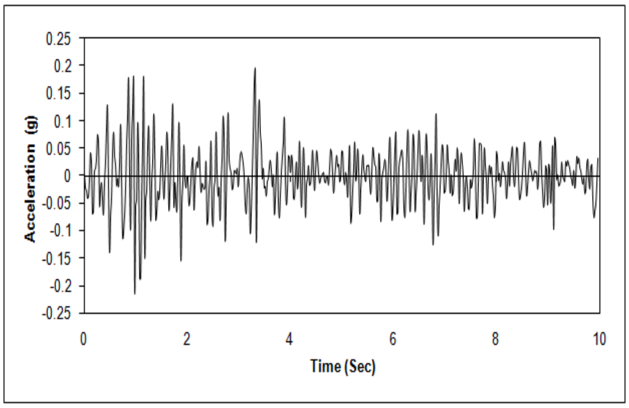

Fig.4.*Vertical element of El centro earthquake*

IV. Model Analysis Results

Following the modeling and dynamic analysis, we extracted results of exerted stress in the body of quay wall, quay wall maximum horizontal displacement, and resulting hydrodynamic pressure in fluid behind the quay wall.Figures 5-9 show the time history of wall maximum horizontal displacement in different modes.Figures 10-14 show the time history of wall maximum principal stress in different modes.

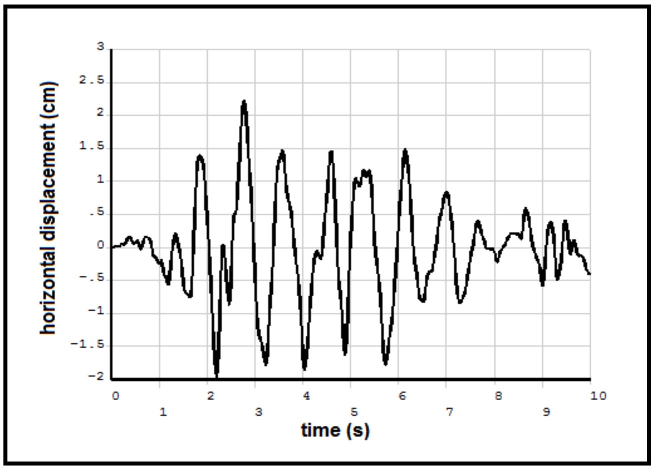

Fig. 5.*Time history of quay wall maximum horizontal displacement with E=15 Gpa*

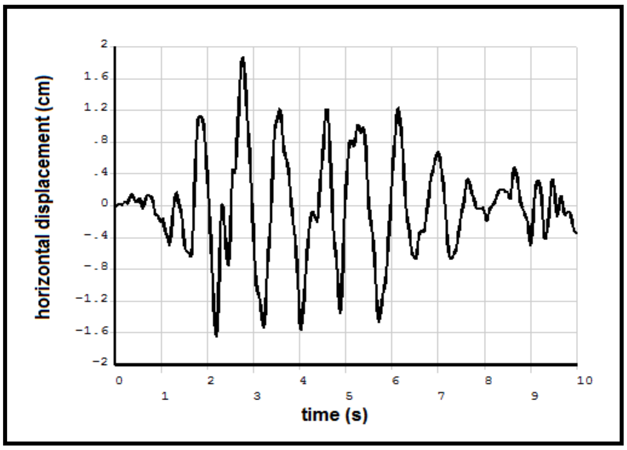

Fig. 6. *Time history of quay wall maximum horizontal displacement with E=20 Gpa*

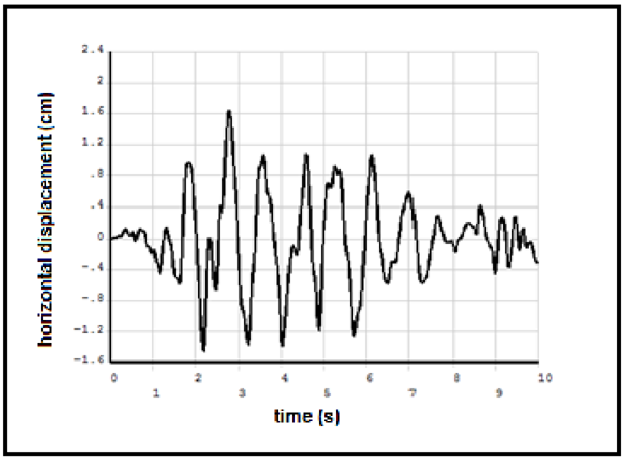

Fig. 7.*Time history of quay wall maximum horizontal displacement with E=25 Gpa*

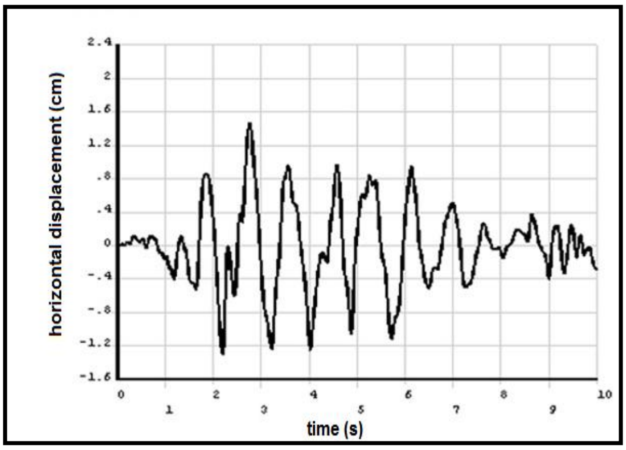

Fig. 8. *Time history of quay wall maximum horizontal displacement with E=30.5 Gpa*

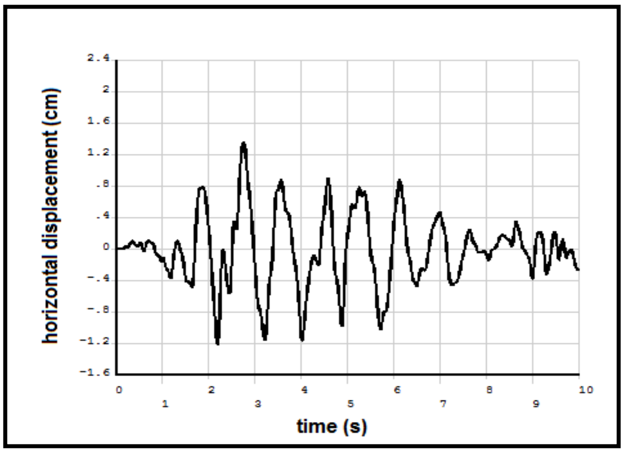

Fig. 9. *Time history of quay wall maximum horizontal displacement with E=35 Gpa*

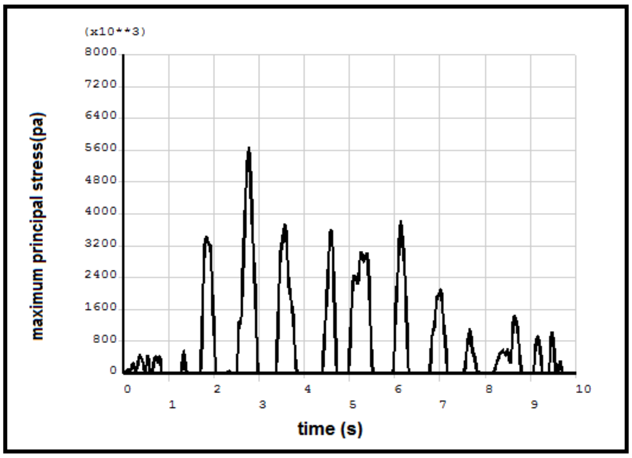

Fig. 10. *Time history of quay wall maximum principal stress with E=15 Gpa*

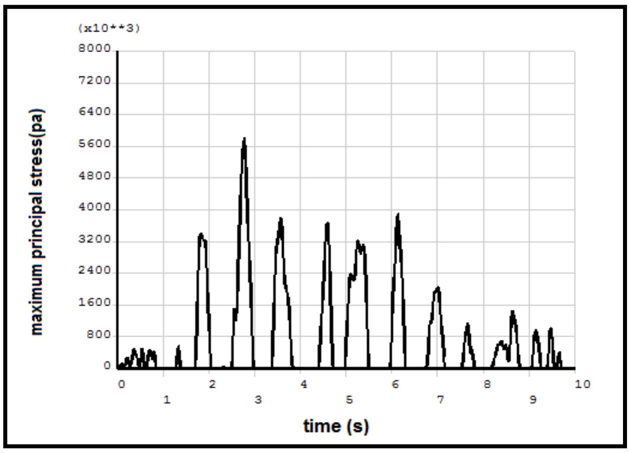

Fig. 11. *Time history of quay wall maximum principal stress with E=20 Gpa*

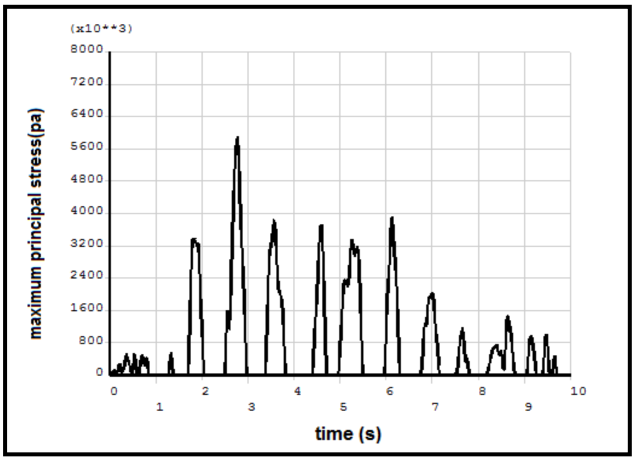

Fig. 12. *Time history of quay wall maximum principal stress with E=25 Gpa*

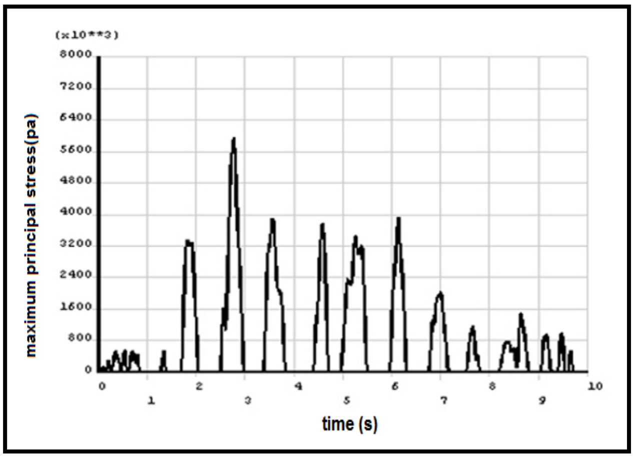

Fig. 13.*Time history of quay wall maximum principal stress with E=30.5 Gpa*

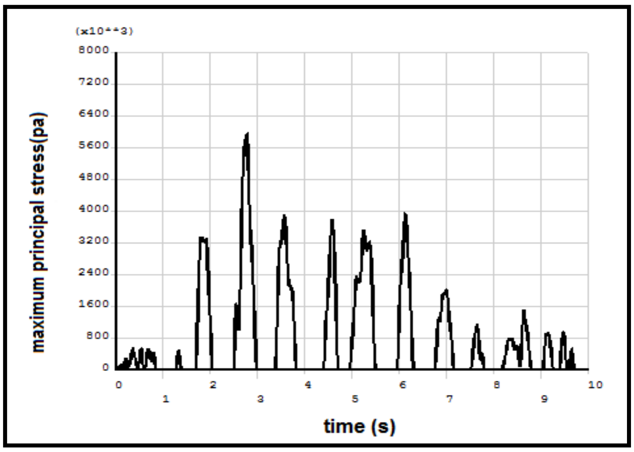

Fig. 14. *Time history of quay wall maximum principal stress with E=35 Gpa*

Figures 15-17 show the location of principal tensile and compressive stresses exerted on body quay wall as well as maximum horizontal displacement.

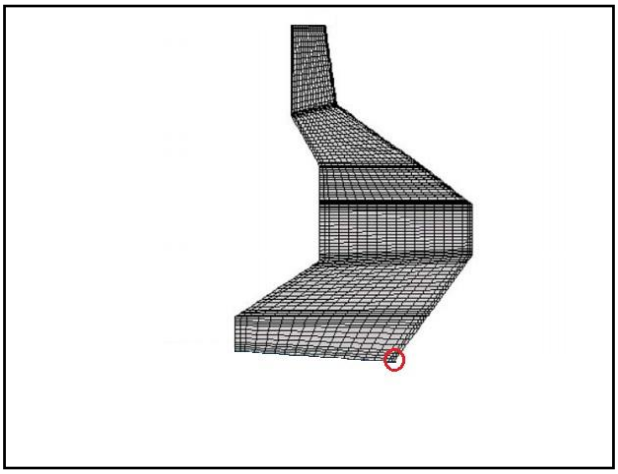

Fig. 15. *Location of maximum principal compressive stress on the body quay wall*

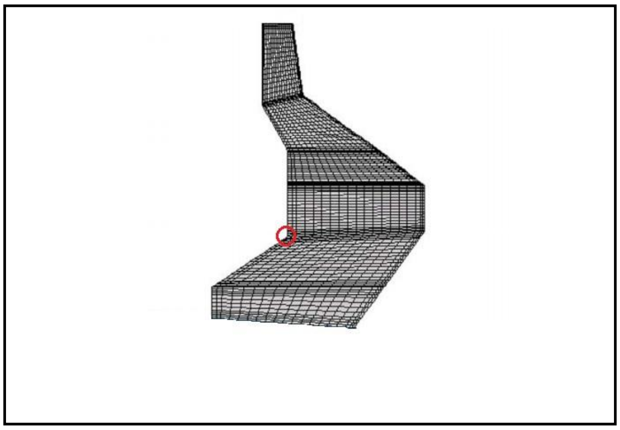

Fig.16. *Location of maximum principal tensile stress on the body quay wall*

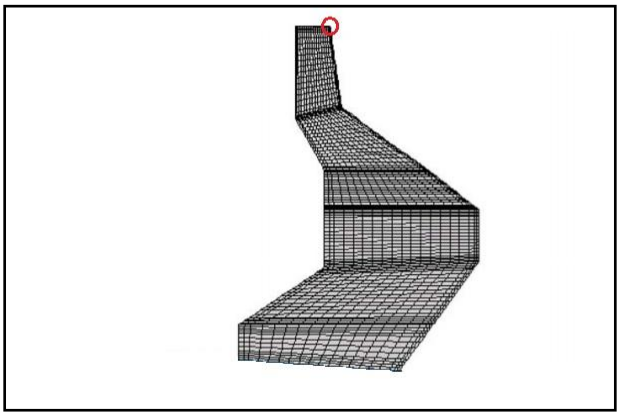

Fig. 17. *Location of maximum horizontal displacement on the body quay wall*

Furthermore, results are provided and compared as diagrams in figures 18-21 to investigate the conditions of principal stresses, horizontal displacement, and hydrodynamic pressure for five modes.

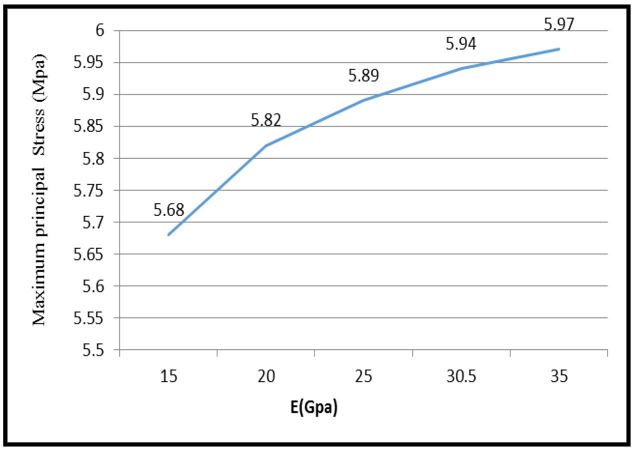

Fig. 18.*Comparison of maximum principal tensile stress on the quay wall in five modes*

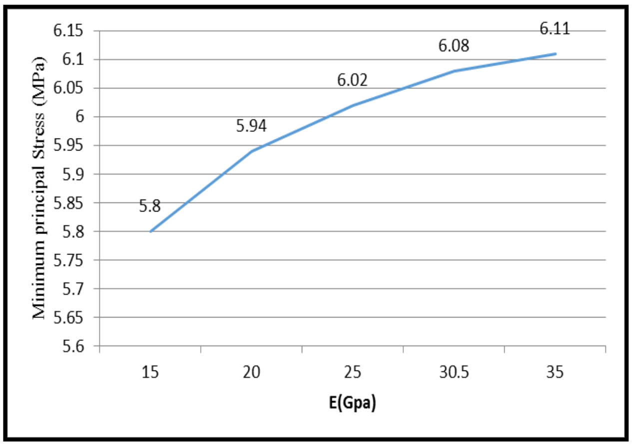

Fig. 19.*Comparison of maximum principal compressive stress on the quay wall in five modes*

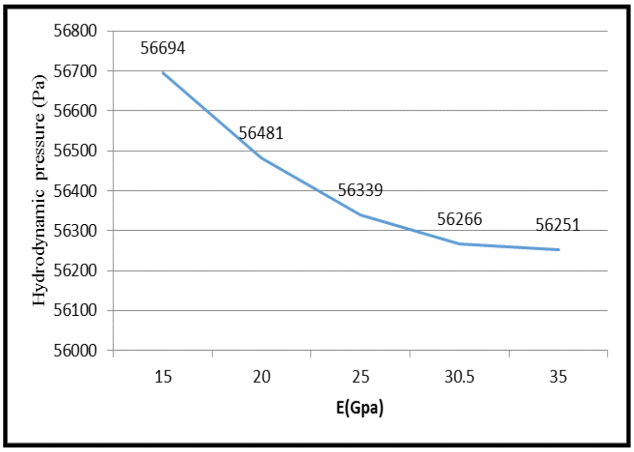

Fig. 20. *Comparison of maximum hydrodynamic pressure exerted on fluid in front of the quay wall in five modes*

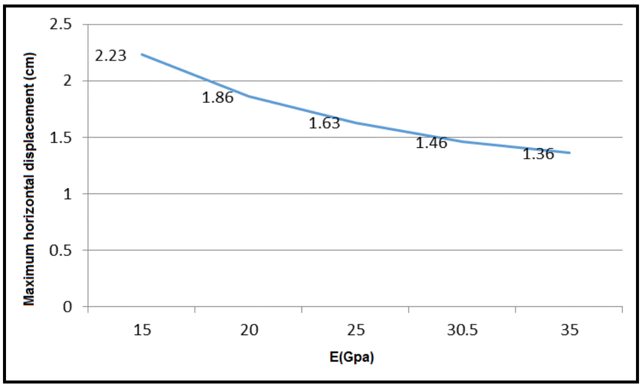

Fig. 21.*Comparison of maximum horizontal displacement of the quay wall in five modes*

V. Evaluation and Comparison of Models

Results from stress, hydrodynamic pressure and horizontal displacement values are presented in table 1 to closely investigate and numerically compare the various modes.Based on the result we can discover the effect of quay wall modulus of elasticity on its seismic response. As results demonstrate when quay wall modulus of elasticity is increased, stress values also increases and displacement and hydrodynamic pressure decreases.It needs to be noted that according to the building codes requirements of ACI, based on$E = 4700\sqrt{f_c}$concrete compressive resistance is directly correlated with concrete modulus of elasticity and concrete compressive resistance values for various amount of modulus of elasticity is provided in table 2.As it is seen in the table, when concrete modulus of elasticity increases, resistance and rigidity of the quay wall also increases.

TABLE II. Numerical values of principal stress and hydrodynamic pressure for various quay wall condition

Quay wall response	E (*GPa*)				
	15	*20*	*25*	*30.5*	*35*
Maximum hydrodynamic pressure (Pa)	5669 4	5648 1	5633 9	5626 6	5625 1
Maximum principal tensile stress (MPa)	5.68	5.82	5.89	5.94	5.97
Maximum principal compressive stress (MPa)	5.80	5.94	6.02	6.08	6.11
Maximum horizontal displacement (cm)	2.23	1.86	1.63	1.46	1.36

TABLE II. Concrete compressive resistance values for various amount of modulus of elasticity of quay wall

E (*GPa*)	15	20	25	30.5	35
Concrete compressive resistance (Mpa)	10.15	18.11	28.29	42.11	55.45

VI. Conclusion

In this paper, quay wall of Antwerp in Belgium was analyzed as a case study through finite element model to investigate the effect of quay wall modulus of elasticity on its seismic behavior. For seismic analysis, horizontal and vertical elements of El Centro earthquake were applied in the model. Following the model analysis, we extracted the results including the principal stresses of the wall, horizontal displacement of the wall, and the hydrodynamic pressure produced in the fluid. In order to investigate the effect of modulus of elasticity, this model was analyzed in various modes. Results indicated that when the wall modulus of elasticity increases, quay wall horizontal displacement decreases which is consistent with our expectation because increased modulus of elasticity contributes to a higher rigidity and because rigidity is conversely related to the displacement, it finally lead to more displacement. It was further discovered that when the quay wall modulus of elasticity increases, quay wall principal tensile and compressive stresses also increase which is considered normal because increased modulus of elasticity lead to higher stress according to the Hook's law.

According to the table of various modulus of elasticity tested in the model, maximum tensile stress values are less than ACI building code requirements and within the acceptable range. However, all maximum tensile stresses derived from various tested modulus of elasticity are more than allowed tensile resistance of concrete and this section in which the tensile stress has highest value need to be somehow strengthened. Because concrete has weak tensile resistance, reinforcement need to be provided in this section to resolve this weakness. Other result is that increased modulus of elasticity created a maximum hydrodynamic pressure in fluid behind the wall. Based on the relationship between concrete compressive stress and modulus of elasticity, with increasing of modulus of elasticity, resistance and rigidity of the wall also increases.

References

[1] H.M. Westergaard, "Water pressure on dams during earthquake", Transactions, ASCE, 98, 1933, pp 418-433.
[2] A.K. Chopra, "Hydrodynamic pressure on dams during earthquakes", J. ENG MEC division, 93 ,1967, pp 205-223.
[3] O.C. Zienkiewicz, B.Iron, and B. Nath, "Natural frequencies of complex free or submerged structures by the finite element method", Symp. Vibration Civ. Engng, Butterworths, 1965, London.

[4] O.C. Zienkiewicz and P. Bettess, "Dynamic fluid-structure interaction: Numerical modeling of the coupled problem," John wiley, New york, 1978, pp 185-193.

[5] A. K. Chopra, "Earthquake response of concrete gravity dams", J. ENG MEC, 96, 1970, pp 443-454.

[6] C.C. Mei, M.A. Foda, and P.Tong, “Exact and hybrid-element solutions for the vibration of a thin elastic structure seated on the sea floor.” Appl. Ocean Res, 1(2), 1979, pp 79-80.

[7] J.F. Hall, and A.K. Chopra, "Hydrodynamic effects in the dynamic response of concrete gravity dams", Earthquake eng structural dynamics 10, 1982, pp 333-345.

[8] B.F. Chen, "The significance of earthquake-induced dynamic forces in coastal structure design", Ocean Eng.22 (4), 1995, pp 301-315.

[9] C.J Lee, R.Dobry, T.Abdoun and B.R.Wu,"Lateral spreading behind a caisson type quay wall during earthquake",In 7th US-Japan Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Liquefaction, 1999, Seattle.

[10] P. Cosyn, E. Van Celst, R. Simons, W. Thibaut, M. Vandamme, "improvement of a classic idea using modern design methods", in un-reinforced concrete, Cement 2001,5,pp 43–7 (in Dutch).