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Seismic Rehabilitation of Pile and Deck Quays Using Structural Fuse
(Case Study of a South Pars Petrochemical Port Quay)

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Abstract
Growthing developments in huge oil and gas extraction resources form one hand and strategic issues on the other hand leads to higher importance of south coasts of iran in the region, therefore, the necessity of constructing quays and other marine structures in these regions is a brief issue. Quays are specific type of marine structures and several code criteria from reliable codes for marine structures shoud be regarded in the design of these structures. The most important constraints which always dominant in the design of structures are their strength against input loads and the cost benefits of the design. Advances have been achieved in the science concerned with the construction and the relation of the loads caused by the earthquake in design of structures in seismic areas such as our country. This makes the structures earthquake resistant design regulations to be completed over the time. Updating the seismic design codes could cause a change in dominant attitude in design of structures. In this research effort, two quay structures pile system, which are utilizing in one of the southern coast of Iran (South Pars Petrochemical Port), and had been designed by the regulations of their build time, are investigated. The quays are evaluated using current codes for performace based design and rehabilitation designs through adding a structural system have been presented. For this, numerical simulation of the quays by finite element modelling is performed using SAP2000 software and numerical analysis is completed. Also, a comparison has been made between the structures' behaviour after the addition of new design and the intact one using the nonlinear analysis results.

Keywords: Seismic Rehabilitation, Quay, Pile and Deck, Nonlinear Behavior, Sturcture Fuse

Introduction

The importance of ports as a connection and transportation point in the development of countries is not hidden to anybody. One of the critical infrastructure components of ports are pile-supported peripheral quays which the maintenance of their serviceability has a significant importance (Fig. 1). In these quays, considering the limited load carrying capacity of vertical piles against seismic excitations, using batter piles as a lateral load resisting member for providing the considered performance level is necessary in many cases.

It could be easily detected from the literature that the seismic behavior of batter pile systems combined with vertical piles is a remarkable topic in academic and professional discussions, and there are also several evidences of interest from the reports regarding the past earthquakes. The main reasons for undesirable behavior of batter piles are high demand from the quay' structure because of its high lateral stiffness, concentration of seismic forces in these members and also stress concentration in the connections between these members and quay's deck, which lead to some failures in pile-cap connections, deck and also the pile. Because of the weak performance of batter piles in several earthquakes, the application of these members was decreased from the end of 20^{th} century and available codes and guidelines regarding the quays prohibited the application of batter piles or in some cases it is just allowed in the situation that enough safety factors are considered in the design (CSLC. ,2003).

In the terms of the lateral behavior of pile and deck systems, in (Seifi Fakher et al.,2007) investigated the behavior of monopoles through the simulation of the structure by using spring elements. The failure mechanisms of the linear springs were also evaluated. In the structural system of a pile and deck quay, the lateral stiffness of the structure could be increased by using batter piles. (Razavi et al., 2006) presented that the application of batter piles in pile and deck quays could decrease the number of vertical piles and improve the financial aspects of design by raising the lateral stiffness and subsequently decreasing the lateral displacement of the structure. However, lessons from the past earthquakes showed that the application of these systems comes with some problems which are so dangerous in some cases. Investigations showed that the special geometry of batter piles leads to low ductility of these members and decreasing the R-factor of the structure. Results demonstrated that these members should not be used in combination of vertical pile groups (Razavi et al.,2006). Different theories are available regarding the application of systems that act only in severe earthquakes. (Razavi et al.,2006). have presented that a defense line could be defined for other members by adding an eccentric bracing system to a pile and deck quay with batter piles, in a way that by yielding of this system in a huge earthquake, this system acts a fuse for the quay and prevents from significant structural damages. The ease of repairing and replacement without structural repair in other regions of the quay is one of the other benefits of these systems (Razavi et al.,2006).

The evaluation of an existing pile and deck quay, which satisfies all the requirement of design codes in time of the design, was performed by (Moharrami et al.,2006). In the aforementioned research, the structure was evaluated by nonlinear static pushover analysis and it was observed that these structures should be evaluated again according to new design guidelines.

The assessment of the behavior of pile and deck quays has also been an interesting topic in international scientific research centers. In (Harn and Mallick et al.,1992) suggested a method for seismic design of pile and deck quays. Afterward, in (Margasson et al.,1997) investigated the bending behavior of piles in pile and deck quays and evaluated the members' behavior till the failure level. In (Seed et al.,1999) examined the lateral behavior of quays supported by pile groups. They recognized that although the conservative design leads to increasing the initial strength of quay structure against lateral loads from the earthquake, it also decreases the ductility of the structure and causes sudden failure in piles and even slabs of the quay. In (Zhang et al.,2002) investigated the dead load effects on lateral behavior and evaluated the harmful consequences of higher levels of dead loads.

After evaluation of the major problems of batter piles, nowadays, some research efforts are tend to identify the weak points their behavior and finding corresponding solutions in a way that it could be used in combination with vertical piles, and by this, the structure will benefit from their advantages, but it will not impact from their disadvantages.

Considering different aspects of the problem, experience from the past earthquakes indicates that the pile-deck connection in the quay is a major source of damage during the earthquake. Quays that were designed according to older design codes may now be seismically deficient according to modern seismic design codes because of their insufficient strength and/or ductility (Razavi et al., 2006). Quays designed according to modern seismic design codes may experience higher demands arising from the effects of seismic vibrations. The aforementioned situations necessitate upgrading the seismic performance of many existing Pile-and-Deck quays to meet the requirements of modern seismic design codes (Shafieezadeh A et al., 2012). Previous studies indicate that although connections designed using older guidelines can maintain cyclic drift demands, they sustain damage and initiate strength deterioration, even at low levels of drift. Therefore, there is an interest in improving the performance of pile connections (Schlechter et al., 2004).

Case of Study

In the past decades, severe damages were observed in quays with batter piles. Thus, it is necessary to investigate the effective aspects of rehabilitation of existing quays to increase their bending capacity while keeping their ductility in the desired level (Harn et al., 2004). Such updating might be needed especially in conventional plastic hinges in pile-deck connections. In this research effort, a quay structure with pile and deck system, which is utilizing in one of the southern coast of Iran (South Pars Petrochemical Port), and had been designed by the regulations of its build time, is investigated (Fig. 1).

Fig 1. Case of Study in South Pars Petrochemical Port

The quay has a group of inclined piles as the lateral load resisting system and also rows of vertical piles. The quay's length is 6.42 m and its width is equal to 6.29 m which is consisted of 12 concrete slabs (12x9 m). Furthermore, 20 vertical piles are in 4 rows which 5 piles are in each row. The height of each vertical piles is equal to 35 meter. Additionally, 16 batter piles are located in both longitudinal and transverse directions as the lateral loading system of the quay. These batter piles have 37 meter length.
In Fig. 2, the structure's plan and the location of batter piles are presented. After evaluating the quay's seismic behavior, modifications in the structure is suggested to improve its seismic performance.

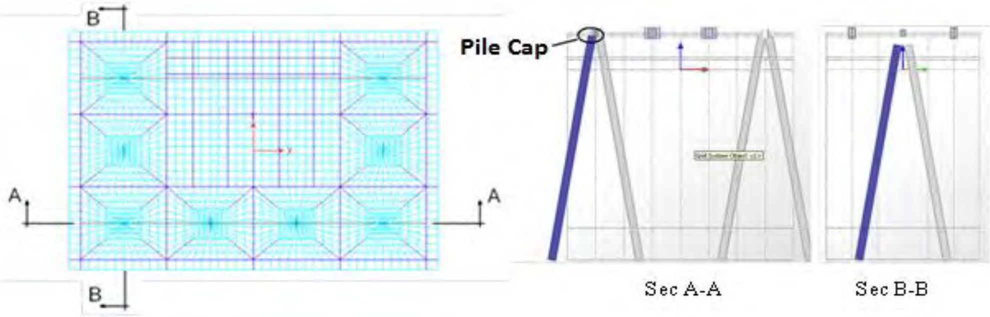

Fig 2. Plan and details of batter piles in the quay

Methodology

The quay is evaluated using current codes for performance based design (CSLC.,2003 and PIANC.,2001), and rehabilitation designs through adding a structural system have been presented. Two different rehabilitation methods are proposed. Figures 3 and 4 present the details of proposed fuse systems and view of corresponding numerical model.

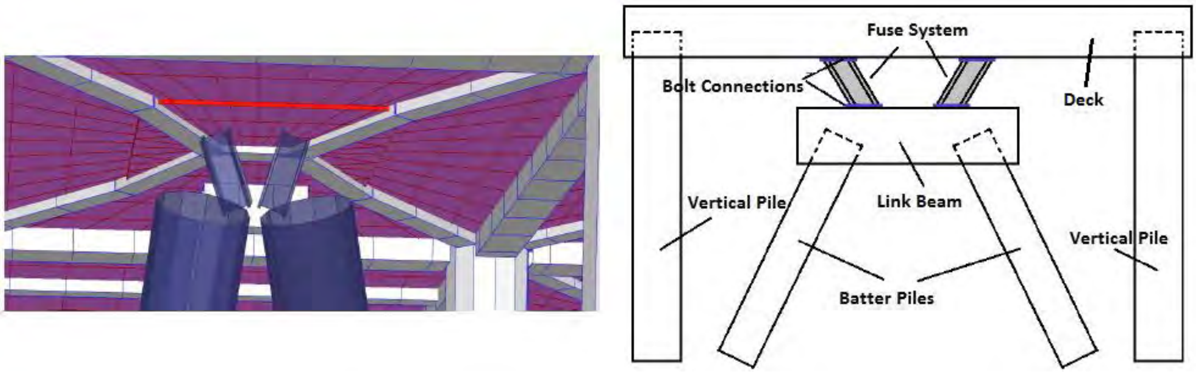

Fig 3. Details of fuse system type 1 and view of the numerical model

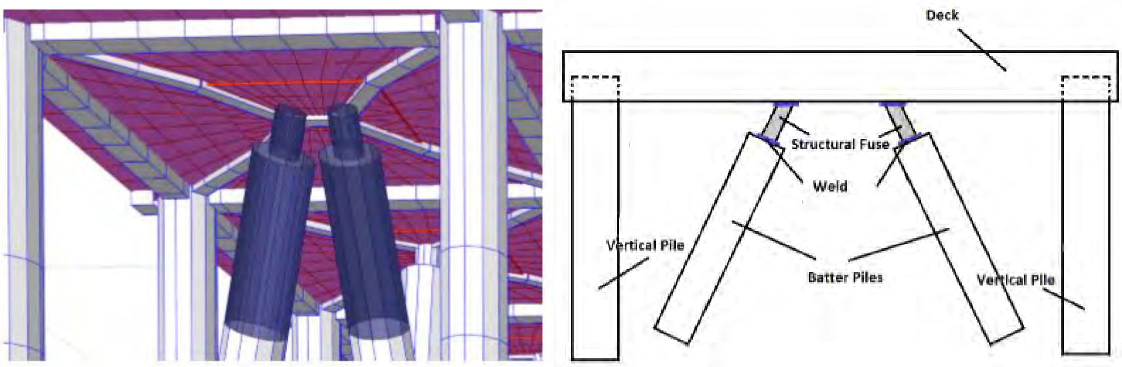

Fig 4. Details of fuse system type 2 and view of the numerical model

Numerical simulation of the quays by finite element modelling is performed using SAP2000 software. Efforts have been made to employ the most proper methods in the numerical simulation to make the analyses results more realistic.

Performance Comparison Before and After Adding the Fuse System

In this part a comparison has been made between the structures' behavior after the addition of new design and the intact one using the nonlinear analysis results. Different parameters such as load-displacement curve, fundamental period, elastic stiffness, base shear, location of first failure mechanism and also members' internal forces are included in the comparison to reach a general judge on the structure's behavior after adding the fuse system.

Pushover curves

First, a comparison is made between the base shear versus displacement of the structure in both cases. Fig. 5-a presents the pushover (base shear-displacement) curve for the structure with and without the fuse system for X-direction loading. A similar comparison for Y-direction is presented in Fig. 5-b. Comparison of the curves from pushover analyzes of intact and rehabilitated structure shows that in both types of fuse system, adding the proposed fuse system leads to a softer general behavior of the structure. Rehabilitated structures experience less shear forces after a certain level of displacement. It should be noted that in the quays with batter piles, decreasing the forces and preventing from undesirable mechanisms in pile-deck connections and also slabs are of major interest.

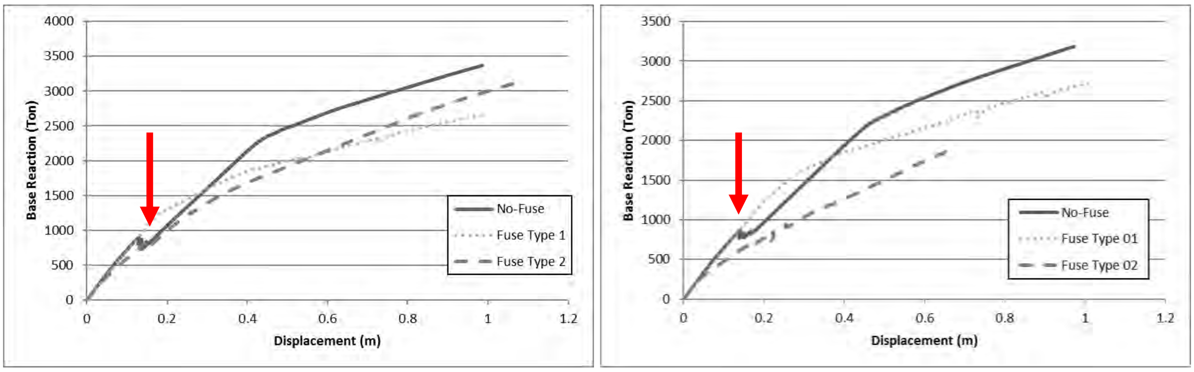

Fig 5. Comparison of pushover curves before and after the rehabilitation: a) X-direction (Left), b) Y-direction (Right)

As it can be seen from above figures, the intact structure experienced the first mechanism in its members by less than 0.2 meter displacement, and the structure lost its uniform behavior and the faced a drop in its strength. This happened because of an extreme load transfer in batter piles which cause some damages in piles especially in pile cap and the pile-deck connections.

Structural behavior parameters

Table 1 presents the comparison between quay's structural responses from pushover analyzes before and after adding the fuse systems. As it was observed in the previous section, both proposed fuse systems were successful in solving the problems from batter piles. Fuse type 1 has better performance in terms of providing additional stiffness for the quay and it is recommended for special cases. On the other hand, fuse type 2 has a softer behavior with much more ductility in X-direction which could be an advantage based on the case.

Moreover, as it can be seen in the table, despite the intact structure which has the first plastic mechanism in a structural member (batter pile), by adding the fuse in both types the first mechanism were happened in the fuse system (under a full control). Furthermore, by using fuse systems types 1 and 2, the fundamental period of the structure is almost kept constant while the maximum base shear in the structure decrease up to 22 and 12 percent, respectively.

Table 1. Comparison of pushover responses of quays

Quay Type	(S) Period	Initial Stiffness (Ton /m)	Base Shear (Ton)	First Yield
Without Fuse	1.549	5539.77	3365.81	Batter Pile
Fuse Type 1	1.590	5094.20	2622.09	Fuse
Fuse Type 2	1.596	3416.63	2944.74	Fuse

Internal forces in quay's piles

In order to have a more precise comparison of quay's structural behavior in the intact state and both rehabilitated structures, a comparison of axial forces, shear forces and also bending moments is performed on four types of piles before and after adding the fuse system in the structure. Fig. 6 presents the location of piles and also beams considered for the comparison in the plan of the structure. The piles are chosen in the way that have different alignments and also load carrying conditions.

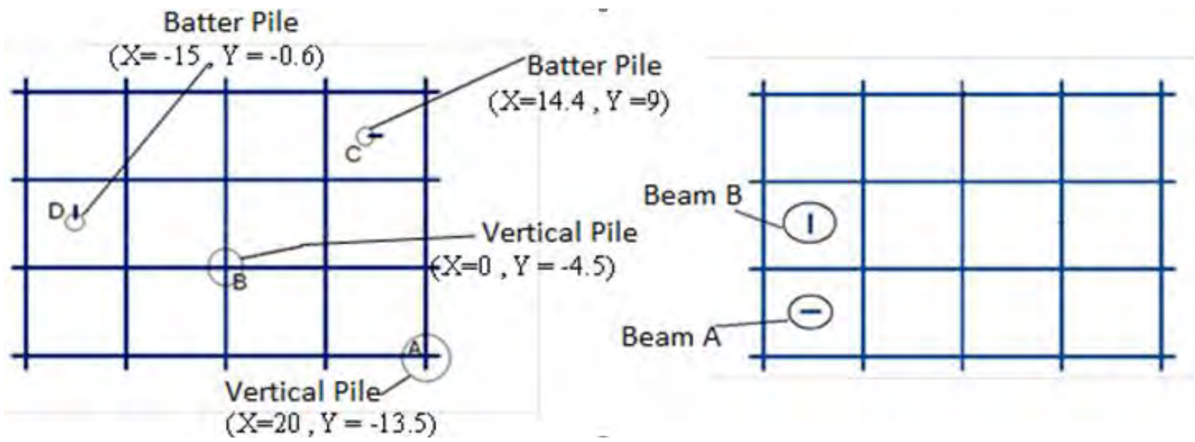

Fig 6. Members chosen for comparison of internal forces in the structure

Fig. 7 shows the comparison of axial forces of studied piles in the quay before and after adding the fuse systems. As it is indicated, in piles A and B, the structures with fuse experience higher average axial forces (22% increase in pile A and 10% increase in pile B) in the members. A similar comparison for piles C and D showed that in both structures with fuse systems, batter piles experience lower axial forces (30 to 50% decrease) and the fuse had an acceptable role in decreasing the batter pile force absorption. It is obvious that the existence of proposed fuse system leaded to a relatively small increase in the axial force of vertical piles and a significant decrease in batter piles' axial forces. Thus, this could prevent from high levels of axial forces in batter piles and deck slabs which decreases the destructive effects of axial forces on the slabs.

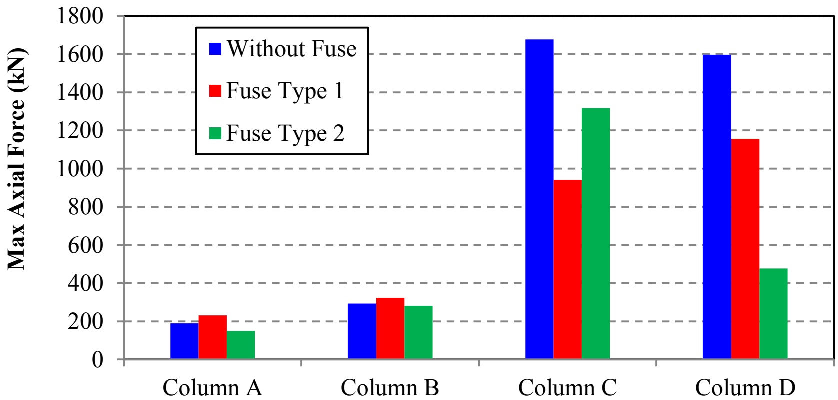

Fig 7. Comparison of axial forces in selected piles in the quay

In Fig. 8, a comparison of shear forces between selected piles is presented. Similarly, Fig. 9 shows the variation of bending moments in the selected piles before and after the rehabilitation. As it is clearly observed, for both shear forces and bending moments, batter piles experience better situation after adding the fuse system. Decrease in the internal forces of these members in some case were more than 50% in comparison with intact structure which is quite important.

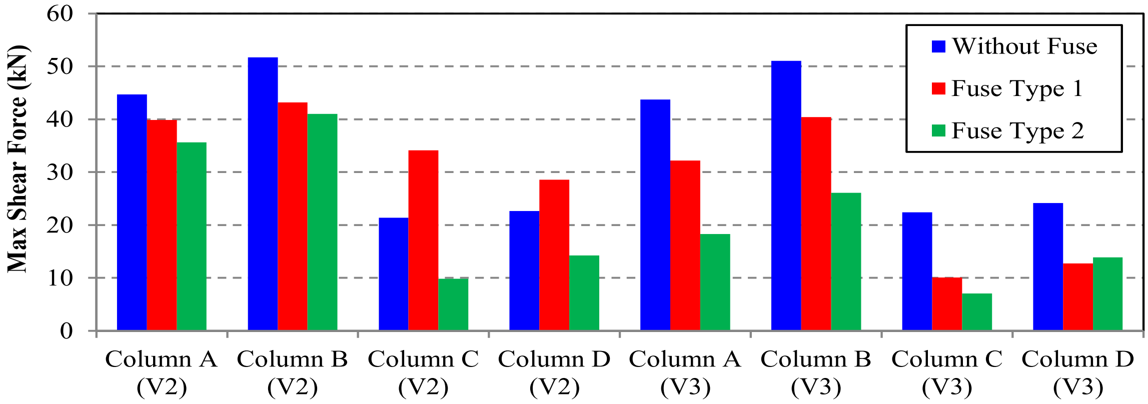

Fig 8. Comparison of shear forces in selected piles in the quay

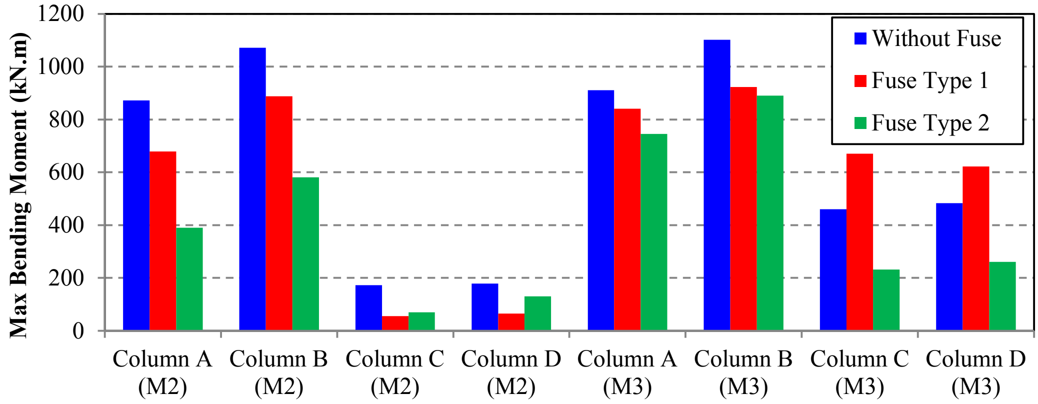

Fig 9. Comparison of bending moments in selected piles in the quay

On the other hand, vertical piles are also experience some additional axial forces which are observed up to 16% averagely for the selected piles. In fact, the fuse system has a transferring action and after reaching the yielding point, transfers some forces to vertical piles through eliminating the collaboration of batter piles.

If the increase of internal forces in vertical piles reach a level that could not be tolerated by vertical piles, adequate resistance should be provided for the pile at least by strengthen some regions which are under the maximum internal forces. However, in the design phase of new quays, it could be defined according to the demand forces after analyzing the structure with built-in fuse system and obtain the optimum cost of the construction.

Internal forces in surrounding beams of deck’s slabs

One of the other important aspects of quay structures is the situation of deck’s concrete slabs which is investigated in the current study. The situation of these slabs is highly important, because, even if the structure maintains its stability after a huge earthquake with minor damages in vertical and batter piles, but, even relatively small failures occur in the deck’s slab, the quay will lose a major part of its serviceability. In the investigation of concrete slabs in this section, since beam members located around each slab, the level of internal forces in the surrounding beams are considered as the criteria for evaluating the effect of fuse system on the structure. For this, two types of beams are selected which their locations were presented before (see Fig. 5). As it can be observed, one of the beams is selected in the longitudinal direction of the quay and the other is in the transverse direction. Moreover, since the axial forces do not have significant role in the beam members, only shear forces and bending moments are comprised in this part. As it is indicated in figures 10 and 11, adding the fuse system to the structure leads to decreasing the shear forces and bending moments in the concrete beams around the slabs of the deck. This reduction in the internal forces in some beams were quite significant which indicates the substantial role of the fuse system.

By investigating the data from these figures, it can be observed that by adding the fuse system type 1, beam A experienced 90 and 66 percent reduction in moments around X and Y directions, respectively. This beam in the structure with fuse type 2 again experienced 90 and 58 reduction in moments for X and Y directions, respectively. For the beam B, fuse 1 decreased the bending moments up to 90 and 26 percent for X and Y directions, respectively. Corresponding values of moment reduction in the structure with fuse type 2 were 90 and 7 percent, respectively. It could be noted that structural fuses transfer the forces from piles to the link element of the fuse and distribute a major part of the loads to the structure in the way that transfer a relatively small moment to the concrete slabs.

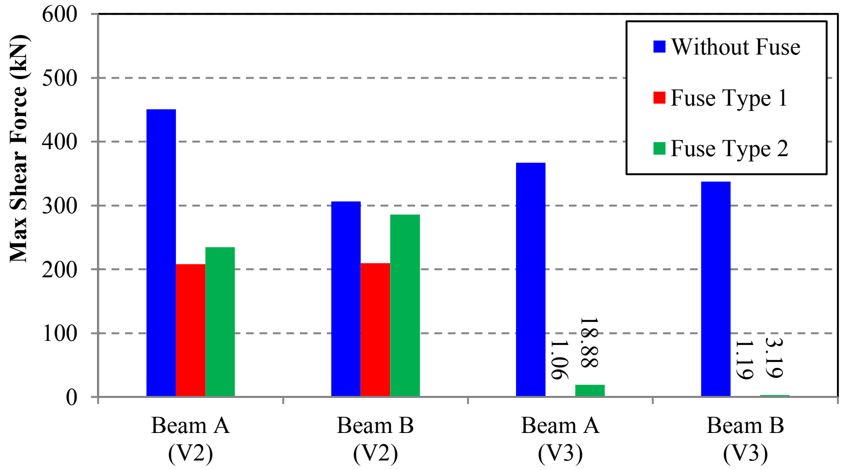

Fig 10. Comparison of shear forces in selected beams in the quay

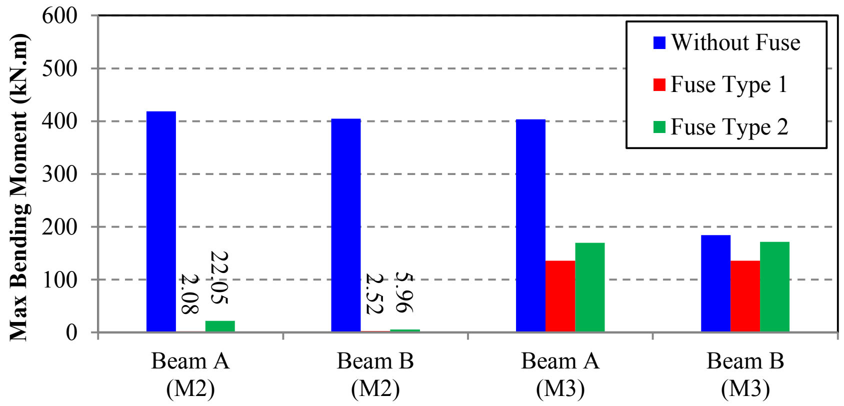

Fig 11. Comparison of bending moments in selected beams in the quay

Additionally, as it is indicated in Fig. 11, fuse system reduced the undesirable forces from batter piles by eliminating their role after the plastic mechanism. Thus, only minor forces transferred to the slab which shows the proper performance of both fuse systems.

Results of Analyses and Investigating the Fuse Performance

By comprising the results of analyses before and after adding the fuse systems, following results could be conducted:

- Applied structural fuse systems properly provided a flexible behavior for the structure while keeping the lateral stiffness and lateral displacement in the same level of an intact structure.

- In the quay without the fuse system, the first mechanism occurs in batter piles; while, in rehabilitated structures with fuse systems, the first plastic mechanism occurs in fuse as a shear mechanism and batter piles as main members of the structure remain safe.
- In quays with fuse system, after the first mechanism in fuse, the first yielded member is the vertical pile. Considering the importance of batter piles as the main lateral load resisting system of the structure, no damage in these members could be noted as an advantage of the proposed fuse systems.
- Comparison of obtained pushover curves shows that the quay without the fuse has presented a higher resistance rather than quays with fuse systems, which could be because of concentration of axial forces in batter piles and increasing of the internal force level in these members; but, this does not necessarily mean that it is an advantage for the structure. Because, the resistance level is only important up to the performance level and more resistance after that is not usable. Moreover, high axial forces in batter piles in the quay without fuse systems requires more considerations regarding in these member which could lead to some problems in the case of existing quays rehabilitation. Some of these considerations include providing adequate shear resistance in the deck to avoid shear punching, providing adequate anchorage length to prevent compressive and tensile failures in the soil, etc. however, in quays with fuse systems, the axial forces in batter piles were limited.
- In quays with fuse system, nonlinear deformations is concentrated in the fuse as a salve member, and the fuse acts as the energy absorption system; while, in the structure without fuse system, plastic hinges will progressively be distributed in piles as the main members of the structure and pile groups act as the energy absorption system.
- In quays with fuse, the axial force of the batter piles is increased by increasing the lateral displacement, and after reaching the mechanism point, the axial forces are remained limited. This shows that the fuse appropriately limited the level of axial forces in the batter piles as the most critical member of the structure. Both compressive and tensile axial forces in batter piles could be the cause for element failures. Hereby, not only the fuse could prevent from buckling, axial and bending failures, but also it can lead to a shorter anchorage length by which could significantly save the costs. Fig. 12 shows the variation of compressive axial force of a batter pile in the quay before and after adding the fuse systems.

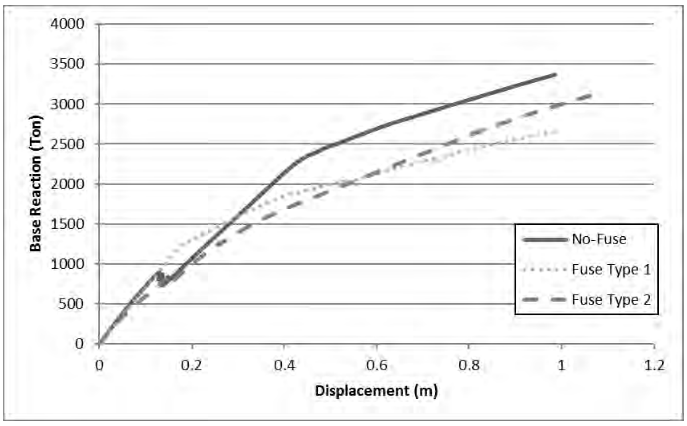

Fig 12. Variation of axial force of a batter pile in the quay with and without fuse systems

Conclusion

The results of nonlinear analyses on finite element model exhibited that by using the fuse systems suggested in the current study, the quay's pushover behavior becomes softer. In fact, the fuse system is able to tolerate large and plastic deformations which reduces the internal

forces in structure's elements. Moreover, unlike the primary structure of the quay which has experienced the first plastic mechanisms in batter piles and other main structural elements, in the rehabilitated structures, the fuse system experiences the first plastic deformations and so less damages occur in other elements specially batter piles.

Moreover, from the comparison of the axial forces in the batter piles before and after adding the fuse system, it can be concluded that the fuse systems properly do their preventive role to avoid transferring the axial loads to the batter piles. However, this leads to a relatively higher axial forces in the vertical piles of the quay.

Of course, for a real usage of fuse systems, perfect control over the mechanism point should be employed in the analysis to make reliability on the fuse performance in the structure. It is recommended to do precise numerical simulations as well as some experimental test to ensure about the structural behavior of the system.

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