External radial stiffeners to improve seismic capacity of pile-supported wharves

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Abstract

Most steel piles suffer from low ductility because of their non-compact cross sections. In this study, ductility of steel piles is improved through external radial stiffeners (ERS) placed in a radial pattern around the external wall of the pile. The ERS would be placed close to the plastic hinge regions. Hysteretic behaviors of piles with and without the proposed stiffener are numerically investigated and compared with each other. Obtained results indicate that ERS would delay local buckling of the steel piles and in this way strength degradation would be alleviated. In other words, ductility capacity of steel piles with ERS would be greatly improved. A parametric study is also carried out to explore optimum geometry and number of required stiffeners. Finally, using a nonlinear static analysis, efficiency of the proposed technique is investigated for a pile-supported wharf located at the Port of Sirik in south of Iran. The proposed technique can be used either in the case of new designs or for retrofit purposes. It turned out that the external stiffeners are substantially beneficial for seismic rehabilitation of highly corroded steel piles.

Keywords: pile-supported wharf, hysteretic behavior, pile, ductility

Introduction

Seismic induced damages on wharves and port facilities can impose significant economical consequences on any country. One quite common type of port structures is pile-supported wharves. Significant efforts have been devoted to achieve a better understanding about seismic behavior of pile-supported wharves and many techniques are proposed to improve their seismic performance. These include batter piles (Gerolymos et al, 2008, Poulos, 2006), modified pile-deck connections (Oyenuga et al, 2001, Lehman et al, 2009), seismic isolators (Leal et al, 2013), hysteretic dampers (Mousavi and Bargi, 2013), and FRP wrapping (Sen and Mullins, 2007), among others. Some of the abovementioned techniques, such as batter piles, application of FRP wrap, and hysteretic dampers, are also well suited for retrofit purposes.

Earlier studies and case histories have indicated that pile-supported wharves are generally vulnerable to three scenarios: lateral spreading, excessive displacement demands on the piles, and large force demands on batter pile-deck connections. In other words, in absence of liquefaction and batter piles, seismic behavior of pile supported wharves can be improved by adopting well suited details for the piles which are the main energy dissipating sources.

According to the current seismic design procedures for the wharves (POLA seismic code, 2010), piles of the wharves are designed to experience inelastic behavior during an earthquake. The same also the case for bridges with pile bents (AASHTO 2008). That is, during a design level earthquake, plastic hinges would develop at the piles. As a result, these elements should have substantial ductility capacity. Unfortunately, most steel piles have non-compact cross sections and are vulnerable to local buckling and strength deterioration during large ductility demands. Commonly diameter to wall thickness ratio of steel piles range from 50 to 80. This high ratio is prone to trigger local buckling. The problem would be more severe in the case of corroded steel piles which have even smaller wall thickness.

In this study, using external radial stiffeners (ERS), a rather new technique is proposed by which, local buckling would be delayed in non-compact steel piles. In the next section, the ERS is introduced and its contribution would be investigated in the subsequent sections. The study is followed by a parametric study to explore the optimum placement and geometry of the ERS. Finally effect of the ERS would be investigated for the pile-supported wharf located in the Port of Sirik. The study is carried out based on numerical simulations and further experimental studies are still required to further validate obtained results of the present study.

External radial stiffeners (ERS)

The ERS composed from a number of steel plates welded to the external face of the steel pile and distributed around the pile in a radial pattern, as shown in Figure 1. Using the ERSs, local buckling would be delayed in plastic hinge regions of the steel piles due to the enhanced local out-of-plane stiffness of the pile wall. In order to validate this claim, two identical piles with and without ERS are considered and subjected to displacement-controlled cyclic loading. The piles are modeled in the general purpose finite element software, Abaqus (2011). Both piles and the ERSs are modeled with shell elements. As depicted in Figure 2, diameter and wall thickness of the piles are 660 mm and 8.6 mm, respectively. Length of the piles is 5m with a fixed base. Yield strength of the used steel is 350 MPa with ultimate strength of 450 MPa. Moreover, before the lateral load, an axial compressive load of 1000 kN is applied to the piles to simulate the gravity loads. All of the above assumptions are made based on the typical piles of the Sirik wharf located in the Port of Sirik. Adopting the AISC's loading protocol (AISC 341-05), the lateral load is imposed on the top of the piles. The loading protocol is also shown in Figure 2.

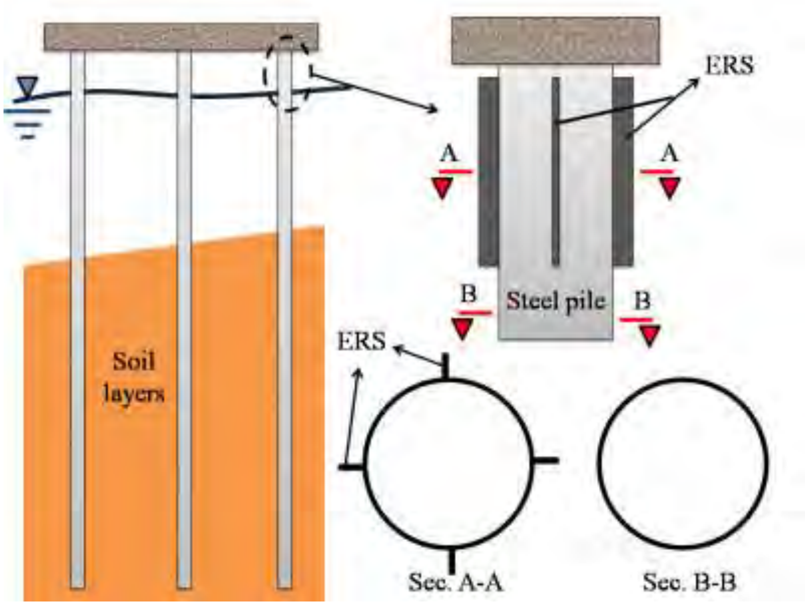

Figure 1. External radial stiffeners (ERS) within the plastic hinge region of steel pile.

In this section four ERS plates, uniformly distributed around the pile, is used with length of 1.5m, width of 100 mm, and thickness of 12 mm. length of the ERS is selected to be roughly 2.3 time the plastic hinge length. Width to thickness ratio of the ERSs is selected to comply with the limitations of seismic compact sections as stipulated in AISC 341 (AISC 341-05). To achieve a seismic compact ERS, with to thickness of the plates should satisfy the flowing relation,

$$\frac{b}{t} \leq 0.3\sqrt{\frac{E}{f_y}} \tag{1}$$

where b and t are width and thickness of the ERS plate, respectively, Young's modulus is denoted by E and f_y stands for yield strength of the steel used in ERS plates. Occurred local buckling at plastic hinge regions of the piles without and with ERS are illustrated in Figures 2 (c) and (d), respectively. It can be seen that ERS has effectively delayed and alleviated the local buckling.
Hysteretic behaviors of the piles in terms of force-displacement and moment-rotation are illustrated in Figure 3 (a). Figure 3 (b) shows the cumulative dissipated energy in the piles. Obtained results indicate that ERS has reduced the strength deterioration to some extent and increased energy dissipation capability of the pile by 65%.
It might be possible to improve contribution of the ERS by modifying its geometric parameters. As a result, the next section is devoted to explore optimum parameters of the ERS.

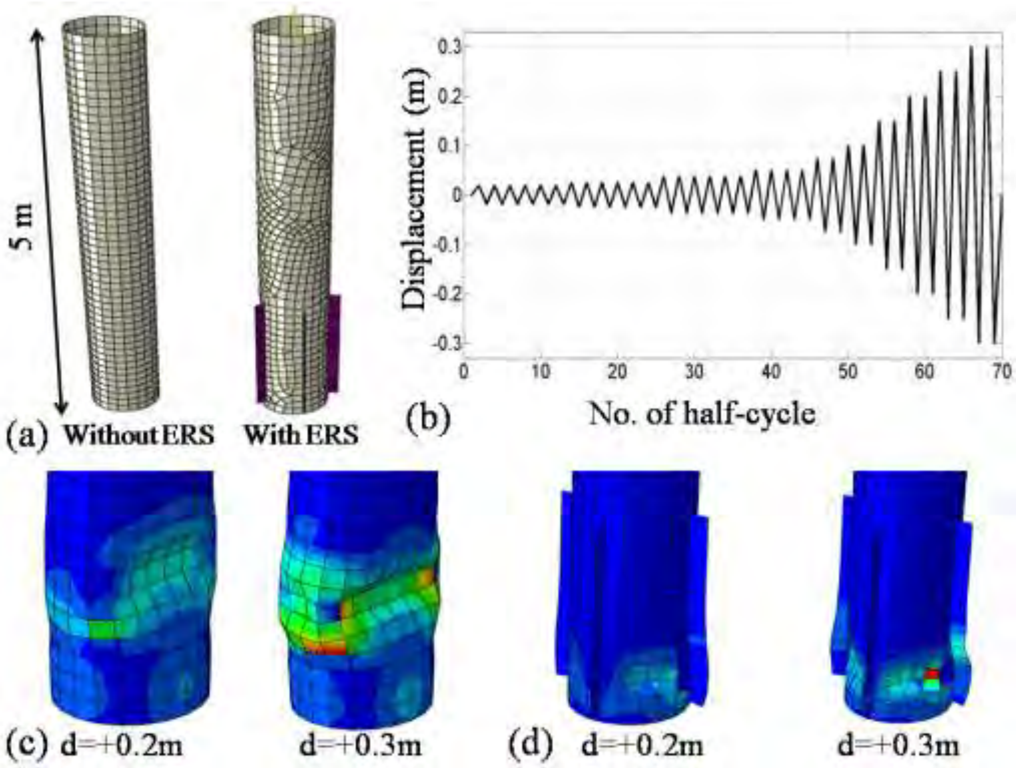

Figure 2. (a) Modeled piles with and without ERS, (b) Adopted cyclic loading protocol, (c) local buckling at the plastic hinge of the pile without ERS, (d) local buckling at the plastic hinge of pile with ERS.

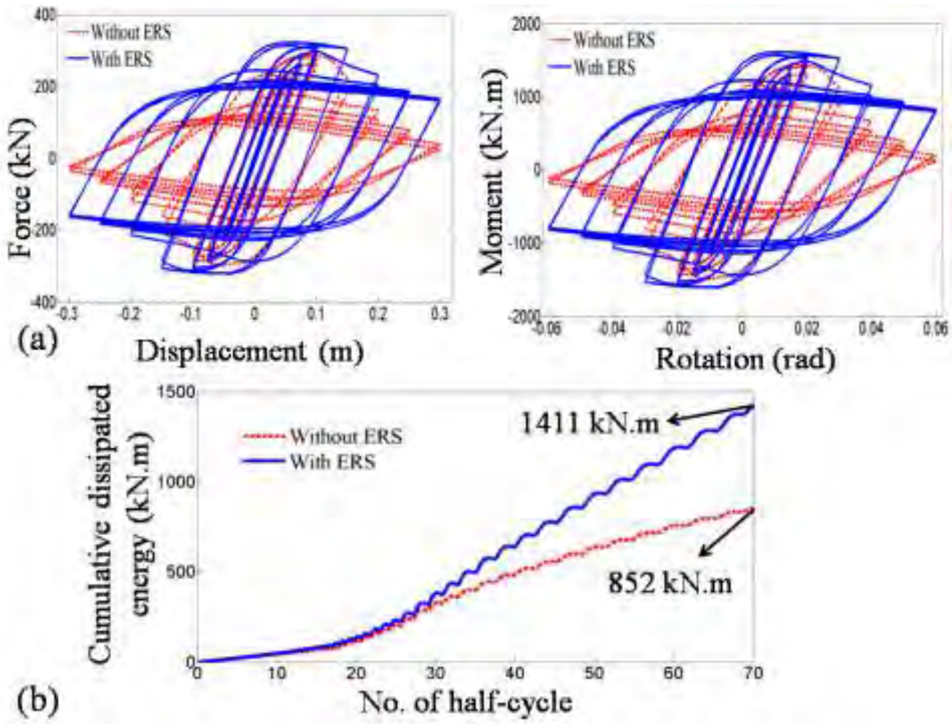

Figure 3. (a) Hysteretic behavior of the pile with and without ERS and (b) the related cumulative dissipated energy.

Optimum parameters of the ERS

In the previous section, it is shown that ERS is effective in improving hysteretic behavior of steel piles. In this section through a parametric study, different parameters of the ERS are optimized to achieve the best performance. The main parameters of the ERS are the number, width, and length of the stiffeners. Effect of the ERS on different piles with different diameters and wall thickness are also investigated. Table 1 represents the considered cases in the parametric study. Cases A to E investigate the required number of ERS plates. Case F would evaluate importance of width of the ERS plate. Cases G and H are intended to explore contribution of the ERS in piles with more compacted cross sections. Importance of the ERS length is investigated in the case I. Finally cases J to L are considered to evaluate performance of the ERS in the case of large diameter piles. Note that in all cases ERS plates are seismically compact, per Equation (1). In all cases, length of pile is 5 m with a fixed base and free top. Other details such as, material properties and cyclic loading protocol, are the same as those discussed in the previous section.

Table 1. Considered cases in the parametric study.

Case	**Pile**			**ERS**			
	Diameter (mm)	Wall thickness (mm)	Axial load (kN)	number	Width (mm)	Thickness (mm)	Length (m)
A	660	8.6	1000	0	-	-	-
B	660	8.6	1000	3	100	12	1.5
C	660	8.6	1000	4	100	12	1.5
D	660	8.6	1000	5	100	12	1.5
E	660	8.6	1000	6	100	12	1.5
F	660	8.6	1000	5	50	6	1.5
G	660	13	1000	0	-	-	-
H	660	13	1000	5	100	12	1.5
I	660	8.6	1000	5	100	12	1
J	1000	13	1500	0	-	-	-
K	1000	13	1500	5	100	12	2.3
L	1000	13	1500	5	150	18	2.3

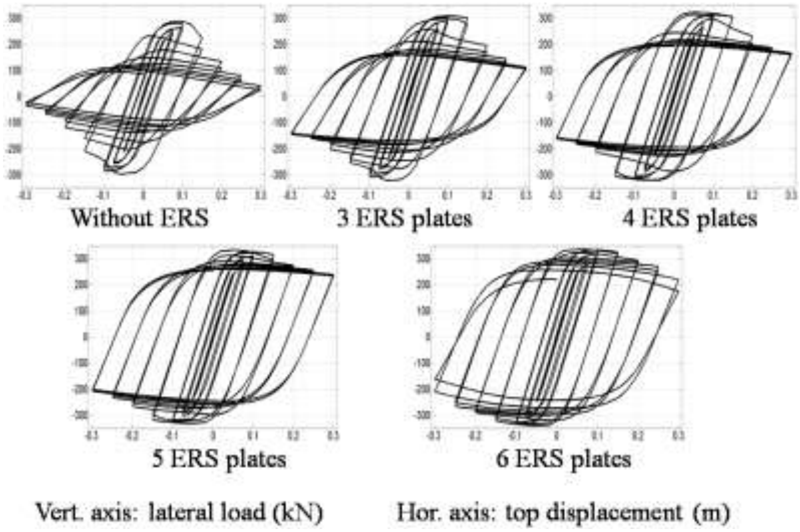

Figure 4. Hysteretic behavior of the pile with different number of ERS plates.

Optimum number of the ERS plates

Figure 4 shows hysteretic behavior of the cases A to E. it can be seen that significant improvement was achieved using 5 and 6 ERS plates. Improvement in the energy dissipation capability of the pile is also depicted in Figure 5 in two different displacement demands. Obtained results indicate that behavior of the pile would be improved by adding further ERS plates up to 5 plates. However, there are no pronounced difference between 5 plates and 6 plates. As a result, 5 uniformly distributed ERS plates can be considered as the optimum number of ERS plates.

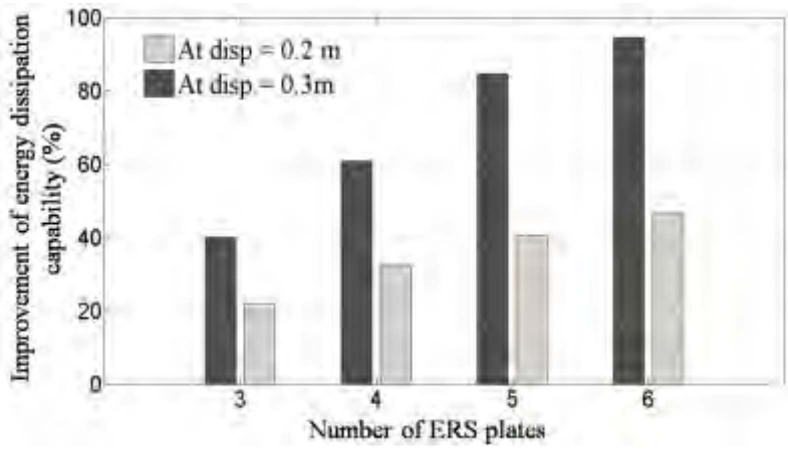

Figure 5. effect of number of ERS plates on the energy dissipation capacity of the pile.

Optimum width of the ERS plates

It is expected that very weak ERS plates cannot prevent local buckling of the pile at its plastic hinge. Previous subsection indicates that width of 100 mm is enough to substantially delay local buckling of the pile. In this subsection it is investigated either smaller widths are also suitable or not. As a result, 5

ERS plates with width of 50 mm and thickness of 6 mm are considered per Case F in Table 1. Hysteretic behaviors of the cases D and F are compared in Figure 6. Clearly ERS plates with width of 50 mm failed to improve hysteretic behavior of the pile. Accordingly, width of 10 mm can be regarded as the optimum width for the ERS plates. As would be discussed in the subsequent subsections, 100 mm width is well suited even in the case of piles with larger wall thickness and larger diameters.

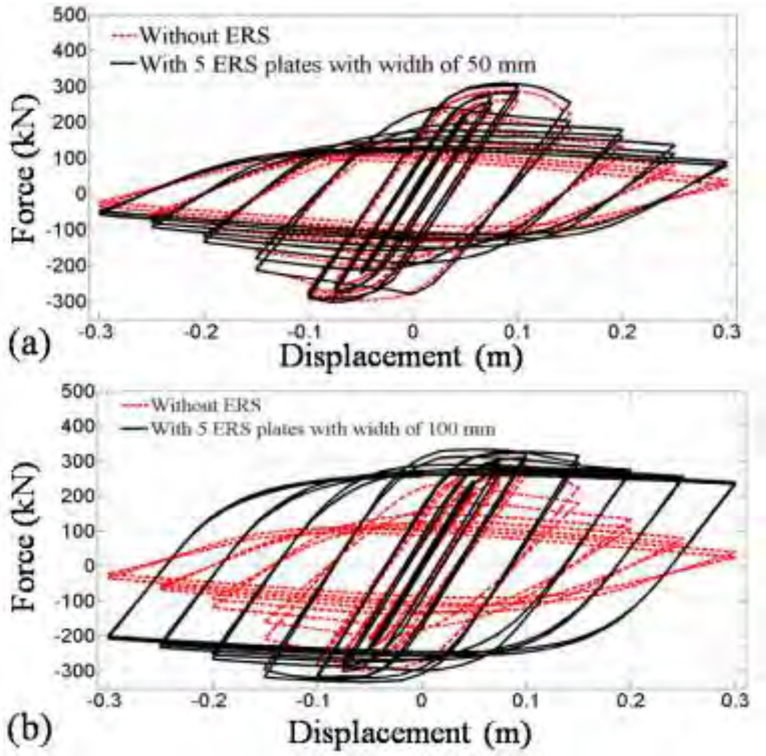

Figure 6. contribution of 5 ERS plates with widths of (a) 50 mm and (b) 100 mm.

Effect of the pile cross section compactness on contribution of the ERS

Piles with thicker walls tend to reveal less strength deterioration and contribution of the ERS might not be pronounced for such piles. In this subsection piles with wall thickness of 13 mm are considered per cases G and H. Obtained results are shown in Figure 7. It is clear that ERS can still improve behavior of the pile, however this improvement is less pronounced compared with earlier cases (piles with thinner walls). Note that thickness of the pile can be significantly reduced during the time due to corrosion. As a result, ERS can be considered as a retrofit alternative to upgrade corroded steel piles which have thin walls.

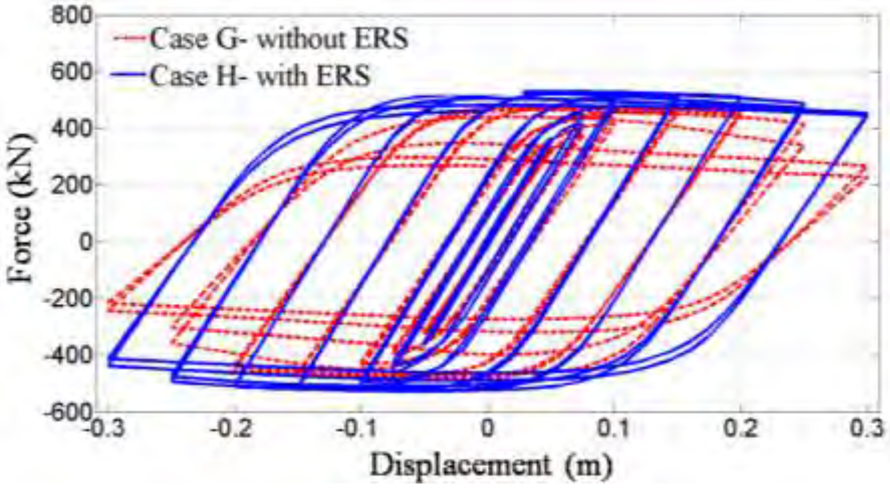

Figure 7. Contribution of the ERS in the case of piles with thicker walls.

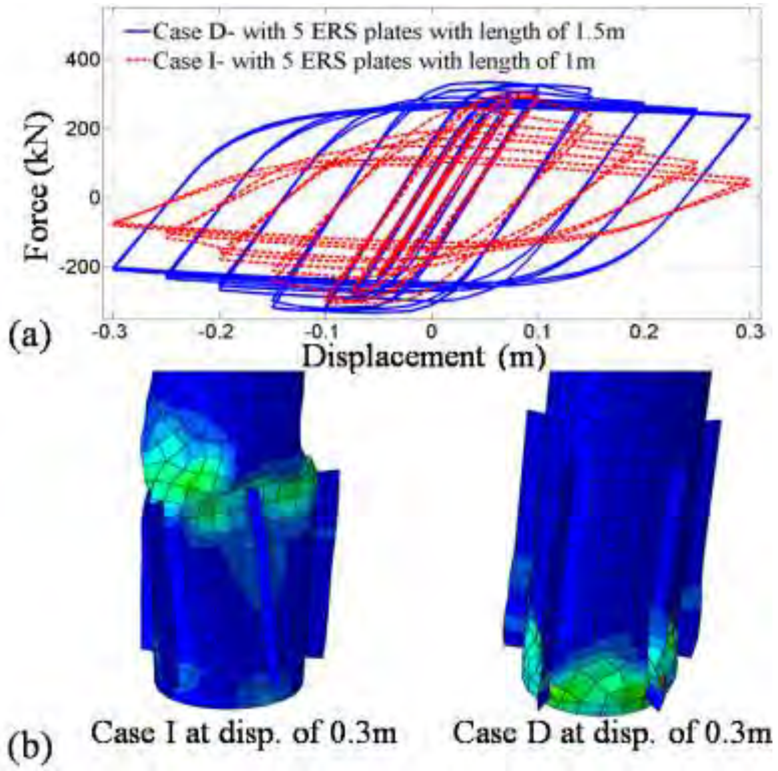

Figure 8. (a) Hysteretic behavior of the pile with different ERS lengths and (b) the related plastic hinges and the occurred local buckling.

Optimum length of the ERS plates

Obviously required length of the ERS plates should be larger than the expected length of the plastic hinge. In this subsection two lengths 1m and 1.5m are considered for the ERS plates, that is cases D and I. Figure 8 compares hysteretic behaviors and the developed plastic hinges in cases D and I. From the hysteretic behaviors it is apparent that the lower length ERSs have failed to improve behavior of the pile. As depicted in Figure 8 (b), this is due to upward movement of the plastic hinge. In other words, in the case of lower length ERS, plastic hinge can be developed outside of the stiffened region in which local buckling can be easily triggered.

According to the obtained results, it is recommended to select ERS plates with a length in the range of 2D to 2.5D (D=diameter of the pile). In this study ERS plates with length of 2.3D show satisfactory performance.

Performance of the ERS technique for large diameter piles

In the previous subsections, the focus was on the steel piles with moderate diameter of 660 mm. contribution of the ERS might be different in stronger piles with larger diameter. As a result in this subsection three piles with diameter of 1000 mm and wall thickness of 13 mm are considered. In Table 1, these piles are labeled as the cases J, K, and L. it can be seen that even for large diameter piles, increase of width of the ERS plates leads to minor improvement. Accordingly, the optimum width of the ERS plate is not sensitive to diameter of the pile.

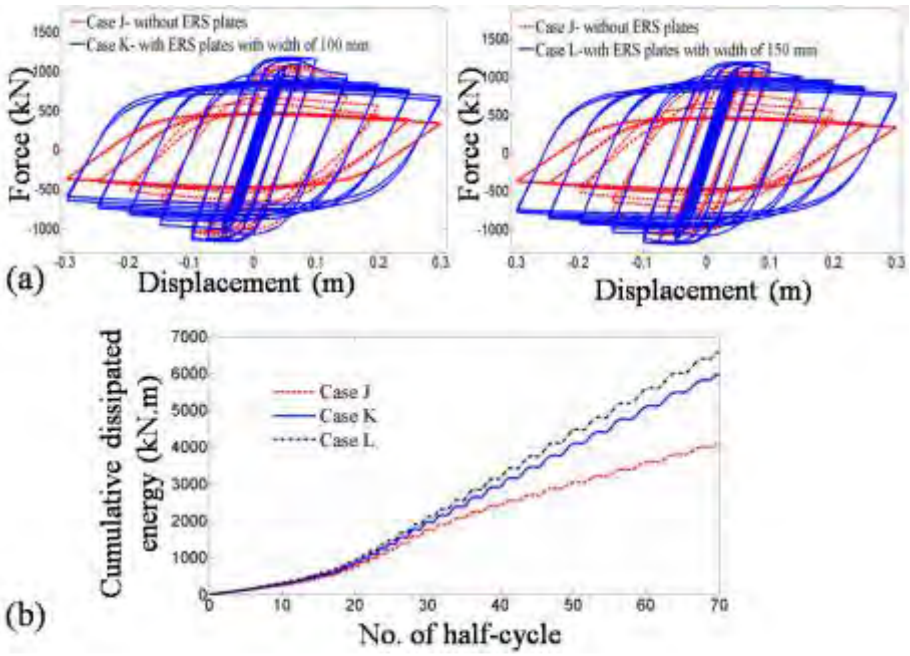

Figure 9. contribution of the ERS in the case of large diameter piles in terms of (a) hysteretic behavior and (b) energy dissipation capability.

According to the carried out parametric study, the optimum width and thickness of the ERS plates are 100 mm and 12 mm, respectively. Besides, length of the ERS plate should be larger than 2D (value of 2.3D is recommended).

Case study on seismic behavior of Sirik wharf with and without ERS

To assess the possible benefits of ERS plates, a pile-supported wharf in the Port of Sirik, south of Iran, is considered. Plan and transverse section of the considered wharf are shown in Figure 10. Details of the wharf are as follow,

- Reinforced concrete deck with thickness of 400 mm.

- Steel piles with diameter of 660 mm and thickness of 13mm. The thickness would be reduced to 8.6 mm after 50 years due to the corrosion.
- Soil profile has an upper layer of loose sand with thickness of 5 m and an underneath thick layer of soft clay.

Further details about the adopted wharf can be found elsewhere (Hosseini, 2015). According to the carried out assessment, the pile could not satisfy Life Safety (LS) performance criteria after 50 years of pile corrosion (Hosseini, 2015). The main reason is the limited plastic rotation capacity of the piles along the axis D which has the smallest above ground length.

In this section, the proposed ERS technique is used to seismic rehabilitation of the piles along the axis D.

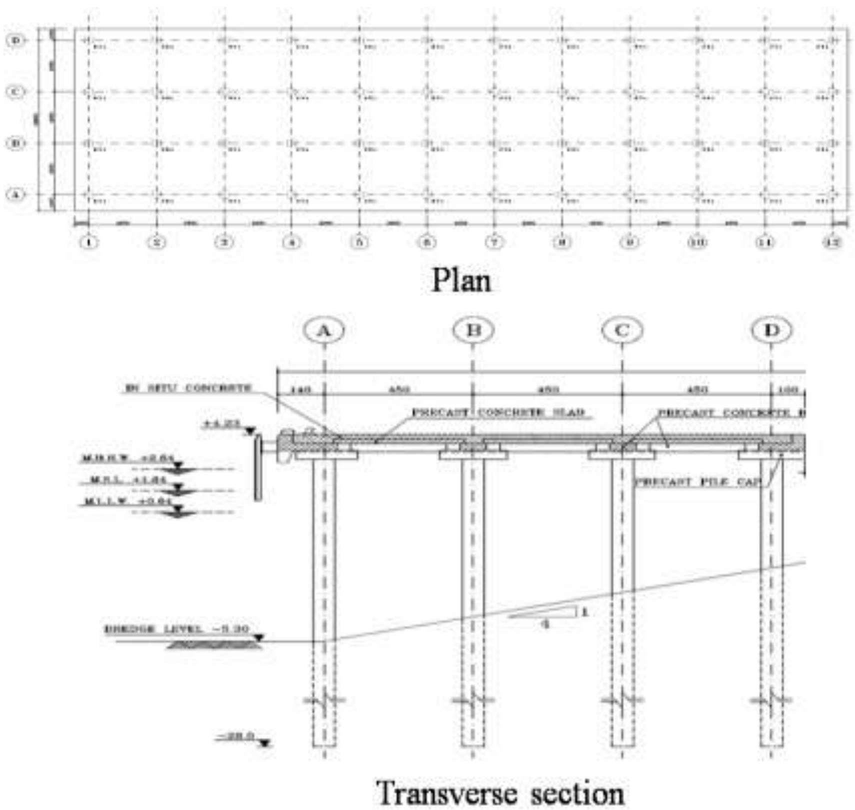

Figure 10. Pile-supported wharf in the Port of Sirik.

The wharf is modeled in SAP 2000 software (SAP 2000, 2012). Soil-pile interaction is considered using the so called p-y, t-z, and q-z elements with the properties specified in API (API, 2000). Figure 11 shows a 3-D view of the modeled wharf and its first two mode shapes. It should be noted that thickness of the pile beneath the sea level is 13 mm as in such environment rate of the steel corrosion is very small compared with that in the splashing zone. On the other hand, wall thickness of the pile above the sea level considered to be 8.6 mm (50 years corroded).

In SAP 2000, all p-y, t-z, and q-z springs are modeled through Link elements with Multilinear Plastic behavior. Piles are modeled with frame elements with plastic hinges and the deck is modeled with elastic shell elements as earlier studies have indicated that deck of the Sirik wharf would remain elastic (Hosseini, 2015).

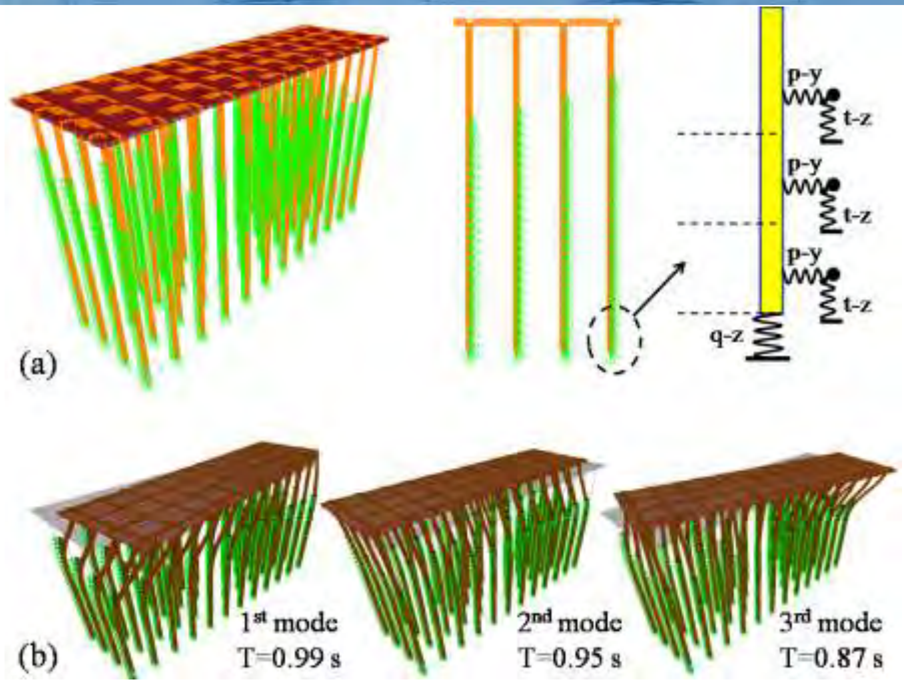

Figure 11. (a) Numerical model of the Sirik wharf and (b) its first three mode shapes.

The piles along the D axis are rehabilitated with 5 ERS plates with length of 1.5 m, width of 100 mm, and wall thickness of 12 mm. as a result, hysteretic behavior of these piles with and without ERS are similar to those discussed earlier in the cases D and A, respectively. Envelop curves of the moment-rotation behavior of plastic hinges of the piles with and without ERS are shown in Figure 12. Plastic hinges are defined from the hysteretic behaviors obtained during the previous section. Plastic rotations corresponding to Collapse prevention (CP), Life Safety (LS), and Immediate Occupancy (IO) criteria are presented in Table 2. It is assumed CP limit state would be achieved when the force drops by 20% at the post-yield segment of the behavior. LS deformation corresponds to 75% of the CP deformation, as suggested by FEMA 356 (2000). Note that acceptance criteria of the pile without ERS are rather close to those proposed by FEMA 356 for HSS columns with non-compact cross sections and the acceptance criteria in the case of pile with ERS are close to those proposed by FEMA 356 for HSS columns with compact cross sections. Therefore, plastic rotations at IO performance are selected according to FEMA 356 such that piles with and without ERS are treated, respectively, as compact and non-compact HSS columns. It should be noted that yield rotations of different piles differ to some extent and the value of 0.005 rad represent the corresponding average value.

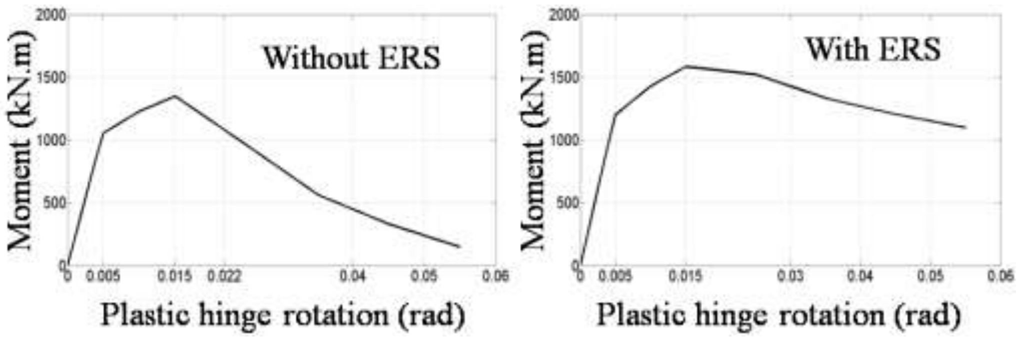

Figure 12. Moment-rotation envelops of the plastic hinges with and without ERS.

Table 2. Acceptance criteria of the pile plastic hinge with and without ERS

performance	Without ERS	With ERS
Yielding rotation	θ_y= 0.005 rad	θ_y= 0.005 rad
IO-plastic rotation	0.25 θ_y	1 θ_y
LS-plastic rotation	2.3 θ_y	5 θ_y
CP-plastic rotation	3.4 θ_y	7 θ_y

Preliminary analyses indicated that no plastic hinge would be developed within the underground length of the piles. As a result ERS plates are only implemented at the upper part of the piles along the axis D. A pushover analyses is done for both models of the wharf (with and without ERS). Obtained capacity curves are depicted in Figure 13 (a). Moreover, Figure 13 (b) shows moment diagram of the piles along the axis 6 at the corresponding target displacement demand. Note that per FEMA 356, target displacement demands of the wharves with and without ERS are 0.32 m and 0.37 m, respectively. ERS provides a positive post-yield stiffness for the lateral behavior of the pile and has resulted in less target displacement.

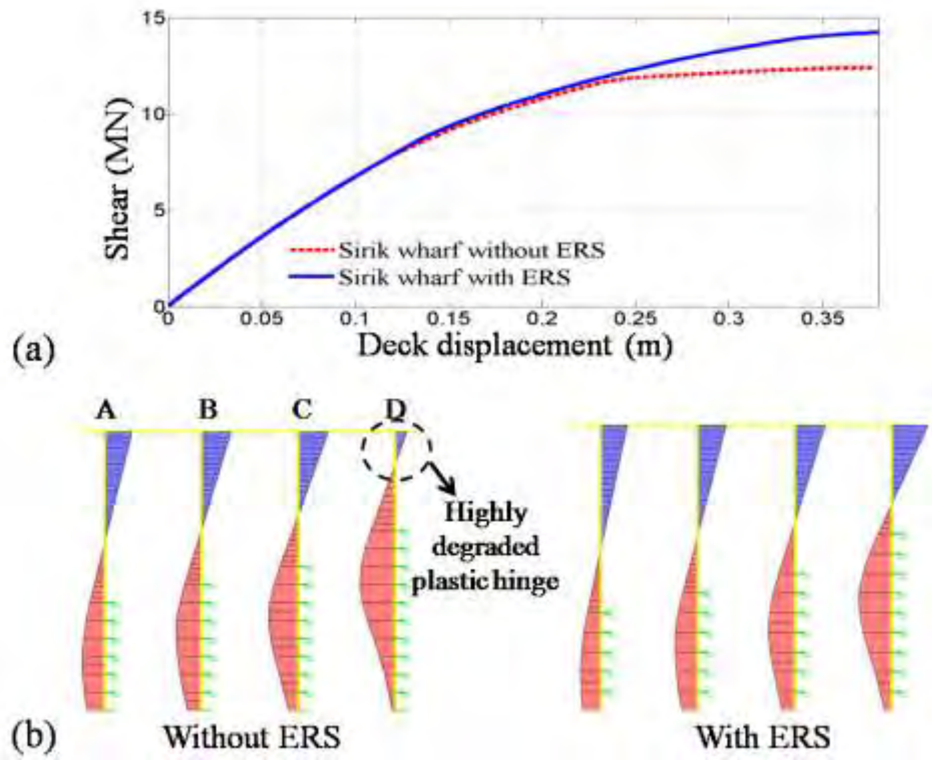

Figure 13. (a) Capacity curves of the Sirik wharf with and without ERS. (b) Effect of the ERS on the developed flexural moments in the piles at the axis 6.

Table 3 shows plastic rotation at the plastic hinge of the piles along the axis 6. Presented values belong to state at which the wharves reach to their target displacements. It is clear that in the case of wharf without ERS, except the pile A6, other piles have failed to satisfy LS performance. On the other hand, in the case of the pile with ERS, virtually all piles have satisfied the LS performance. However, the pile C6 has surpassed LS performance to some extent. While this is quite small and ignorable, as an alternative ERS plates can be considered for not only axis D's piles but also those placed along the axis C.

Table 3. Plastic rotations of the piles along the axis 6 at the target displacement.

wharf	Pile A6	Pile B6	Pile C6	Pile D6
Without ERS	$0.01= 2\theta_y$	$0.0149=3\theta_y$	$0.021=4.2\ \theta_y$	$0.046=9.2\theta_y$
With ERS	$0.006=1.2\theta_y$	$0.011=2.2\theta_y$	$0.0146=2.9\theta_y$	$0.018=3.6\theta_y$

It is interesting to note that, while ERS has been used only along the piles at the D axis, imposed demands on other un-stiffened piles have also reduced. Accordingly, after 50 years of pile corrosion, ERS plates can be considered among the rehabilitation alternatives for the Sirik pile-supported wharf.

Conclusions

A new rehabilitation technique is proposed by which seismic capacity of pile-supported wharves can be significantly improved. In the proposed technique, external radial stiffener (ERS) plates would be placed around the steel piles of the wharf. The ERS plate should be only placed close to the plastic hinges. ERS increases out-of-plane stiffness of the wall of the piles and subsequently local buckling would be delayed. Local buckling is the main reason of the occurred strength degradation in the hysteretic behavior of steel piles, especially because most steel piles have non-compact cross sections. Obtained results indicate that strength deterioration of the piles with ERS would be greatly reduced. To optimize geometrical parameters of the ERS, a parametric study is carried out using quasi-static cyclic analyses on FE models of the piles with different ERS configurations. It turned out that 5 ERS plates results in satisfactory pile performance. Each plate should be seismically compact with width of at least 100 mm and thickness of at least 12 mm. length of the ERS plates should not be less than 2D (D=pile diameter) with a recommended value of 2.3D.

A case study is carried out using a pile-supported wharf located in the Port of Sirik. After 50 years of corrosion, wall thickness of the piles would be significantly reduced and the wharf cannot satisfy LS performance anymore. Contribution of the ERS technique is investigate for the Sirik wharf by placing the ERS plates only at the most critical piles (the piles with shortest above ground length). Using a nonlinear static procedure, it is found that ERS plates can increase post-yield stiffness of the capacity curve of the wharf and in this way improve its dynamic stability. Besides, due to the enhanced plastic rotation capacity of the stiffened piles, these piles can easily pass the LS criterion.

while promising results have been obtained during this study, the authors believe that further numerical and experimental studies are still required to fully understand behavior of steel piles stiffened with ERS plates.

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