Required patch plate thickness for corrosion-damaged steel piled jetty to recover its seismic performance

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ABSTRACT

A finite element modeling for a steel pipe pile repaired by patch plates is developed to examine the patch plate thickness required to provide the same load carrying capacity and ductility as those of an intact pipe pile can be provided. Pushover analysis of the whole FE model of a piled jetty is performed to study performance of repaired steel piles. Further, the pushover analysis of a cantilever FE model of repaired pile is carried out to propose an empirical formula to determine the required thickness of patch plate for corroded steel piles with different structural sizes and thickness reductions. By performing the time history response analysis of a simplified whole FE model of a piled jetty, it is shown that seismic behavior of the steel piled jetty repaired by patch plate designed by the proposed formula is almost the same as that of the intact piled jetty.

1. INTRODUCTION

Recently, many steel structures constructed in the period of high economic growth have been deteriorated, and the importance of maintenance of stocked structures has been understood in Japan. The corrosion is one of the main factors of deterioration and damage in steel structures, and harbor steel structures are surrounded by a severely corrosive environment. If corrosion prevention of harbor steel structures is not enough, load carrying capacity and seismic performance of those structures may decrease.

The Japanese design specifications for harbor facilities (The Ports & Harbors Association 2007) were revised from the allowable stress design to the performance-based design in September 2007. But it is the present condition that the buckling strength and the seismic performance are not yet considered in the repair design with patch plates.

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The authors examined the corroded steel pipe repaired by steel patch plate subjected to cyclic bending in both experimental and analytical studies (Furunishi 2011). Furthermore, cyclic bending behavior of the repaired steel pipe was analyzed by using a cantilever model subjected to axial forces, and required thickness of patch plate was considered (Furunishi 2012). Then, the whole FE model of a steel piled jetty repaired by steel patch plate was used to study load carrying capacity and ductility, and the required thickness of patch plate was examined by using pushover analysis (Furunishi 2013).

In this paper, the equivalent cantilever FE model is used to examine required thickness of steel patch plate. This equivalent model is the cantilever model extracted from the upper part of a steel piled jetty. Pushover analysis of repaired piles with various parameters is performed, and a design formula on a required thickness of patch plate is proposed. By performing the time history response analysis of a simplified whole FE model of a pile jetty, it is verified that repaired steel piled jetty with patch plate thickness obtained from this formula satisfies the target seismic performance.
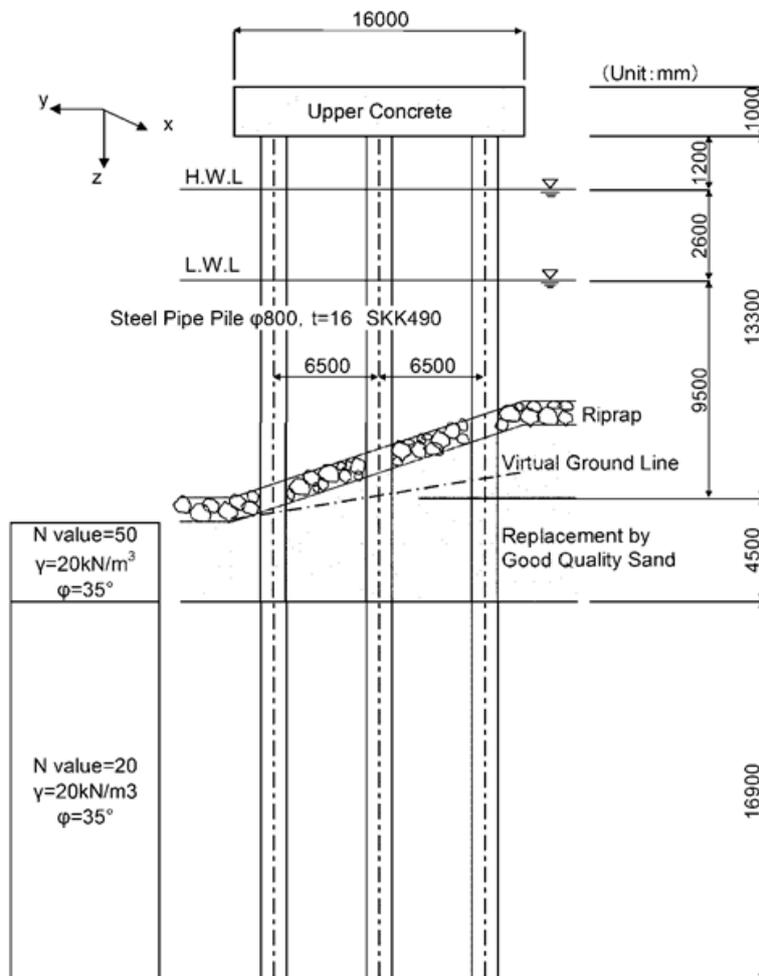
Fig. 1 Piled jetty used in this study

2. PUSHOVER ANALYSIS OF STEEL PILED JETTY

2.1 Steel Piled Jetty

The steel piled jetty shown in Fig. 1 (The Headquarter of Structure Design in KAJIMA Corporation 2007) is studied. The pile interval in the x-direction is also 6.50 m. The tips of piles are supported by bedrock. The vertical load acting on the upper concrete members is its dead load and over-load. The upper layer of submarine soil is soft soil, therefore, it is improved by replacement of good quality sand as shown in Fig. 1. In Fig. 1, N-value, unit weight and internal friction angle of each stratum of submarine soil are shown. Virtual ground line is given according to the Technical Standard and Commentaries for Port and Harbor Facilities (The Ports & Harbors Association of Japan 2007).

2.2 Pushover Analysis Model of Steel Piled Jetty

Fig. 2 shows the pushover analysis model of the piled jetty shown in Fig. 1. The outline of analysis is described in the following.
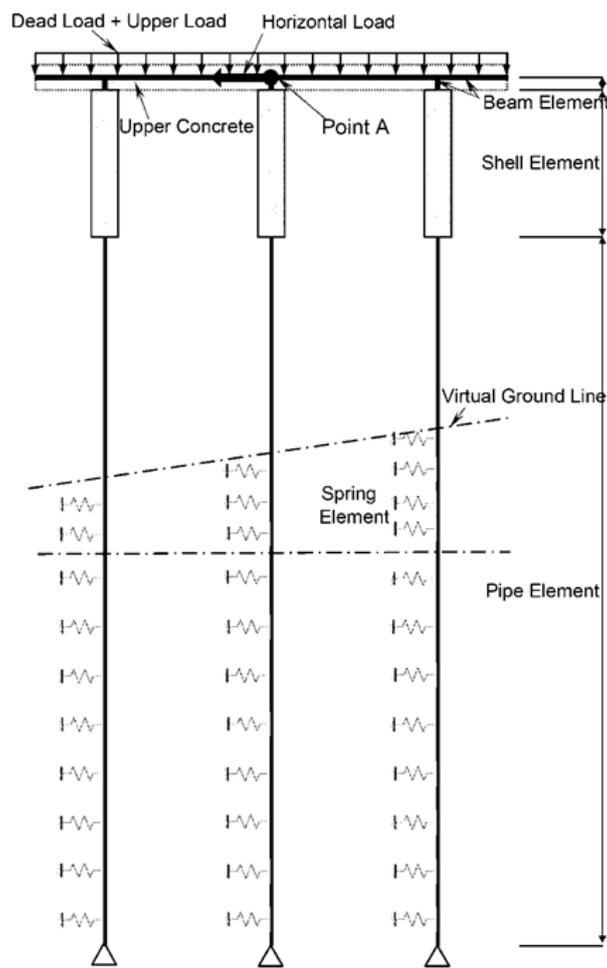

Fig. 2 Whole model of piled jetty

1) A half cross-section of steel pile is considered in the model because of symmetry conditions about the vertical plane of the piled jetty.
2) The upper concrete member is modelled as an elastic beam.
3) The pile head is modeled by shell elements because the occurrence of local buckling in the pile head is expected due to corrosion and large bending moment.
4) Rigid beam elements are used to connect shell elements of piles to the beam elements of the upper concrete members. Although piles are filled with concrete at the pile head, rigidity of filled concrete is not considered in this study.
5) The pile below the pile head modelled by shell elements is modeled by elasto-plastic pipe elements.
6) Subgrade reaction is modeled by spring elements. Its load-displacement relationship is shown in Fig. 3 as elasto-plastic spring element. In Fig. 3, P_s is the force on a spring, δ_s is the displacement of a spring, and k_H is the spring constant. P_{pmax} is the upper limit value of subgrade reaction, which is calculated from the passive earth pressure at each spring position.
7) The bottom of each steel pipe pile is restricted in the vertical direction.
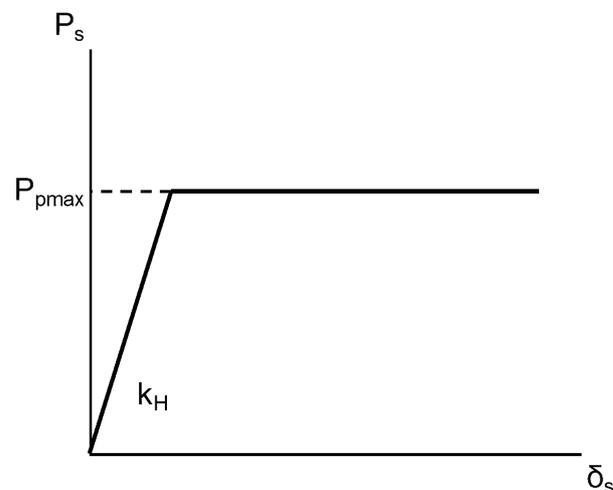8) The forced horizontal displacement is given to the point A of the upper concrete as shown in Fig. 2.

Fig. 3 Load-displacement relationship of spring

2.3 Finite Element Model

The shell element part for the whole piled jetty model is detailed in Fig. 4, and the finite element model is shown in Fig. 5.

In the finite element model, a half pipe section is divided into 60 elements in the circumferential direction, the pitch length in the axial direction is 20 mm, and therefore the shape of each element is approximately a square. The thickness-reduced pipe is modeled based on measured corrosion-distribution of steel pipe pile exposed to the

ocean environment (Tamura 2005, Fujii 2006). The shell element part of corroded pipe and patch plate is modeled by 4-node thin shell elements. The fillet welding between corroded pipe and patch plate is modeled by elastic springs with the stiffness proposed by Chen (2011). The top of the shell element part is connected with beam elements, and the bottom of the shell element part is connected with pipe elements. These connections are represented as multi-point constraints.

The grade of steel pipe pile is SKK490 specified in JIS A5525, and that of steel patch plate is SM490 specified in JIS G3106 having the same mechanical properties as steel pipe pile. Mechanical properties of these steels are shown in Table 1.
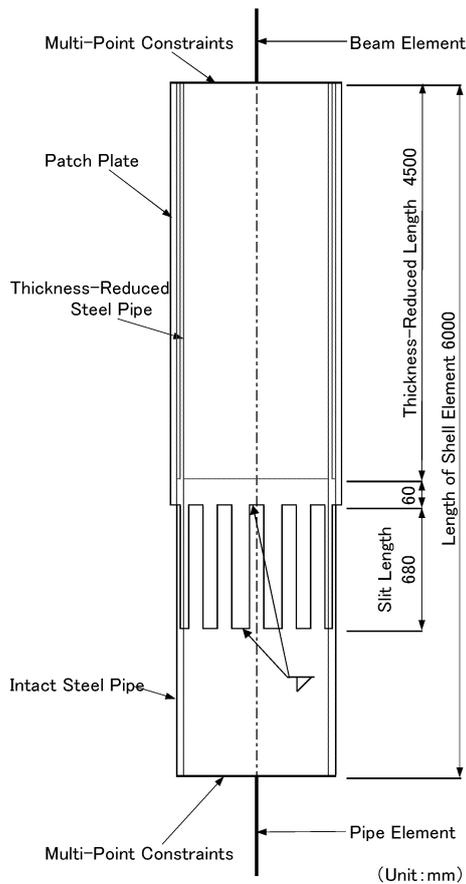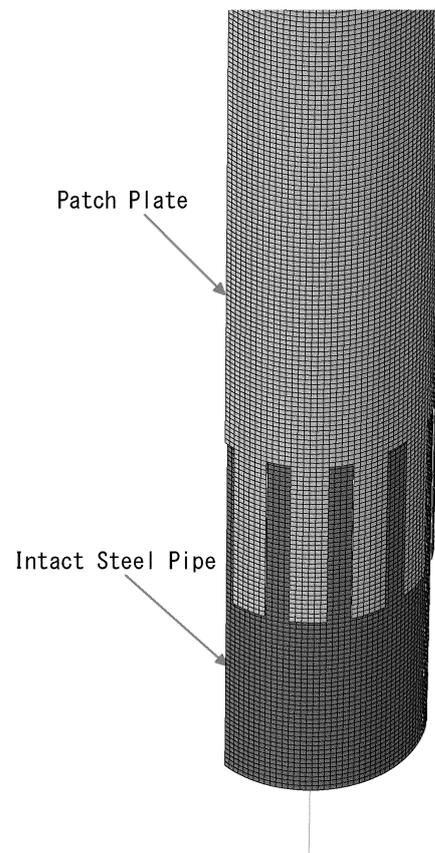

Fig. 4 Details of shell element part   Fig. 5 Shell element model

Table 1 Mechanical properties of steels

Material	Yield stress (N/mm^2)	Tensile strength (N/mm^2)	Young's modulus (N/mm^2)	Poisson's ratio	Strain at tensile strength (%)
SKK490	315	490	2×10^5	0.3	18
SM490					

A general purpose FE program, Abaqus (Dassault systèmes 2010), is used in this analysis. The stress-strain relation is bi-linear. The linear Ziegler kinematic hardening law is used as the hardening law after yielding. Residual stress and initial imperfection are not considered in this study because it is the main purpose that the performance of steel piled jetty repaired by steel patch plate is investigated.

2.4 Distribution of Corrosion Thickness

The corrosion distribution in the longitudinal direction is modelled to include the actual corrosion distribution characteristics. At the same time, the thickness in the circumferential direction is assumed to be uniform.

The general corrosion distribution feature of marine steel structure is shown in Fig. 6. The corrosion profile can be divided into splash zone, tidal zone, sea water zone, and soil zone.
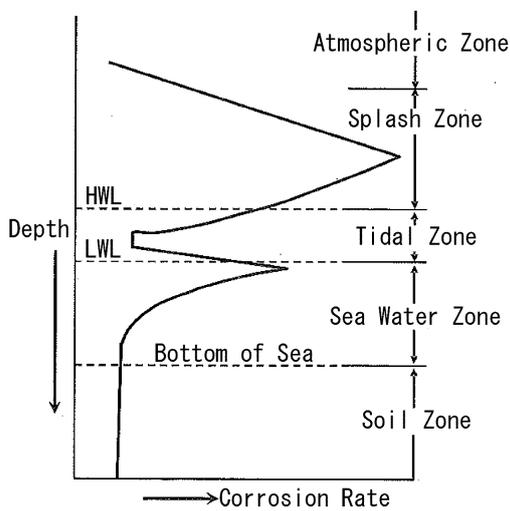
Fig. 6 Typical corrosion rate profile of marine steel structure (Japan Society of Civil Engineers 2009)

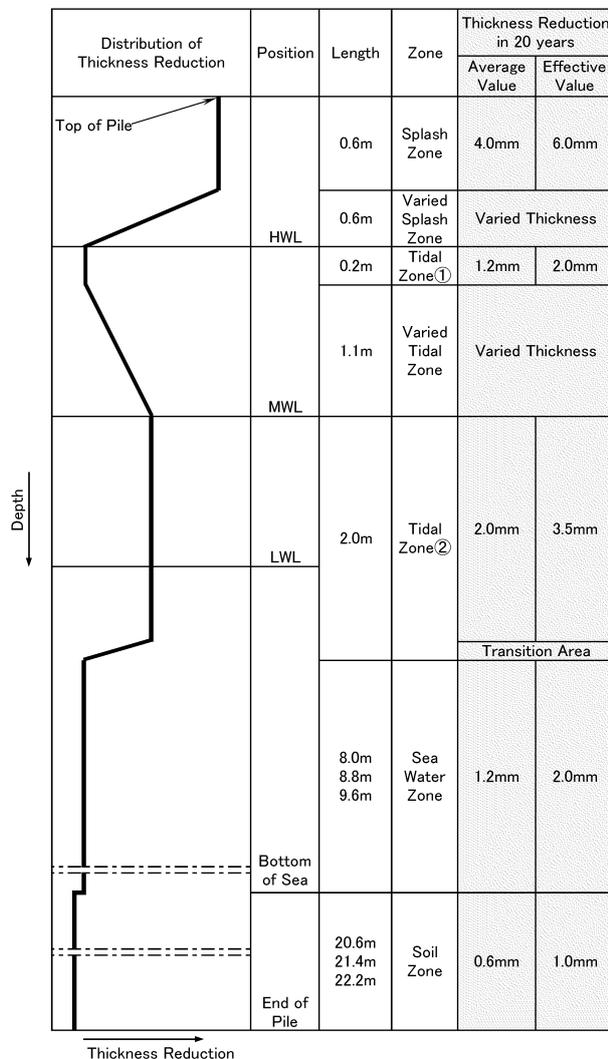| Distribution of Thickness Reduction	Position	Length	Zone	Thickness Reduction in 20 years	
				Average Value	Effective Value
Top of Pile		0.6m	Splash Zone	4.0mm	6.0mm
	HWL	0.6m	Varied Splash Zone	Varied Thickness	
		0.2m	Tidal Zone①	1.2mm	2.0mm
		1.1m	Varied Tidal Zone	Varied Thickness	
	MWL				
	LWL	2.0m	Tidal Zone②	2.0mm	3.5mm
				Transition Area	
		8.0m 8.8m 9.6m	Sea Water Zone	1.2mm	2.0mm
	Bottom of Sea				
		20.6m 21.4m 22.2m	Soil Zone	0.6mm	1.0mm
	End of Pile				

Fig. 7 Distribution of thickness reduction

There are several studies about actual corrosion characteristics on steel members in marine environments. Tamura (2005) and Fujii (2006) studied corroded thickness of exposed steel pipe in marine environments for about 20 years, and Yamasawa (2008) studied corroded thickness of exposed steel angle members. In this paper, corroded thickness is estimated by using the results of Tamura (2005) and Fujii (2006).

To evaluate load carrying capacity of corroded steel pipe accurately, effective thickness acquired from average thickness and its standard deviation is generally used so that the effect of non-uniform thickness can be considered. The effective thickness for load carrying capacity evaluation is expressed as follows (Coastal Development Institute of Technology 1997) :

$$t_R = t_{ave} - \alpha S,\tag{1}$$

where t_R and t_{ave} are effective thickness and average thickness, respectively; S is its standard deviation; and α is a constant (α=1.0~1.5). Since in the analytical model, unevenness of steel pipe thickness due to corrosion is not considered, to include the effect of unevenness, the effective thickness is used in the analysis model. The effective thickness obtained from Eq. (1) is shown in Fig. 7. The analysis is executed by using the value of α=1.0, and the standard deviation of corrosion thickness is based on the results from Tamura (2005) and Fujii (2006).

2.5 Analytical Procedures

The finite element analysis includes both material and geometrical nonlinearities. At the beginning, the vertical load is applied to the upper concrete member, and then the forced displacement is given to the upper concrete member in the horizontal direction.

A required patch plate thickness is determined to satisfy the following conditions.
1) The maximum horizontal force (P_{max}) in the case of repaired steel pile should be higher than that in the case of an intact steel pile.
2) The absorbed energy in the case of a repaired steel pile should be more than that in the case of an intact steel pile. Here the absorbed energy of the intact steel pile is calculated as the shaded area of load-displacement curve up to the
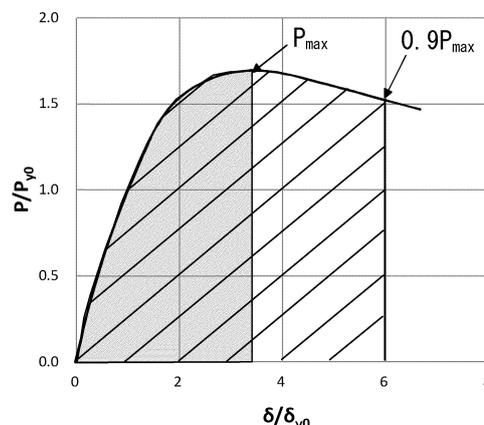

Fig. 8 Area of energy

maximum horizontal force as shown in Fig. 8, and that of the repaired steel pile is calculated as the area under the load-displacement curve until the load decreases to $0.9P_{max}$ (Fig. 8). In the case of a repaired steel pile, the load is allowed to decrease to $0.9P_{max}$.

3) In practice, the top part of pile is filled with concrete. The allowable strain provided in the Japanese Specifications of Highway Bridges (Japan Road Association 2012) for a concrete filled steel column is used as the allowable strain of steel pile, which is $5\varepsilon_y$, where ε_y is a yield strain.

Table 2 Pushover analysis results of piled jetty

Thickness of Patch Plate (mm)	Maximum Load		Area of Energy	
	P(kN)	P/P_{max0}	A	A/A_0
Intact Pipe	P_{max0}= 1044	1.000	A_0= 4.03	1.000
Reduced Pipe	659	0.631	2.44	0.605
8	1007	0.965	4.20	1.042
9	1063	1.018	4.48	1.112

The results from pushover analyses are shown in Table 2. It is found from Table 2 that the patch plate with a thickness of 9 mm satisfies the above-mentioned conditions. The load-displacement curves are shown in Fig. 9 for both an intact pipe case and a repaired pipe case, and deformed shapes after the ultimate load are shown in Fig. 10. In Fig. 9, P and δ are normalized by horizontal force and displacement of upper concrete when the top of intact pile yields, respectively, and t_p and t_s are thicknesses of pipe and patch plate, respectively.
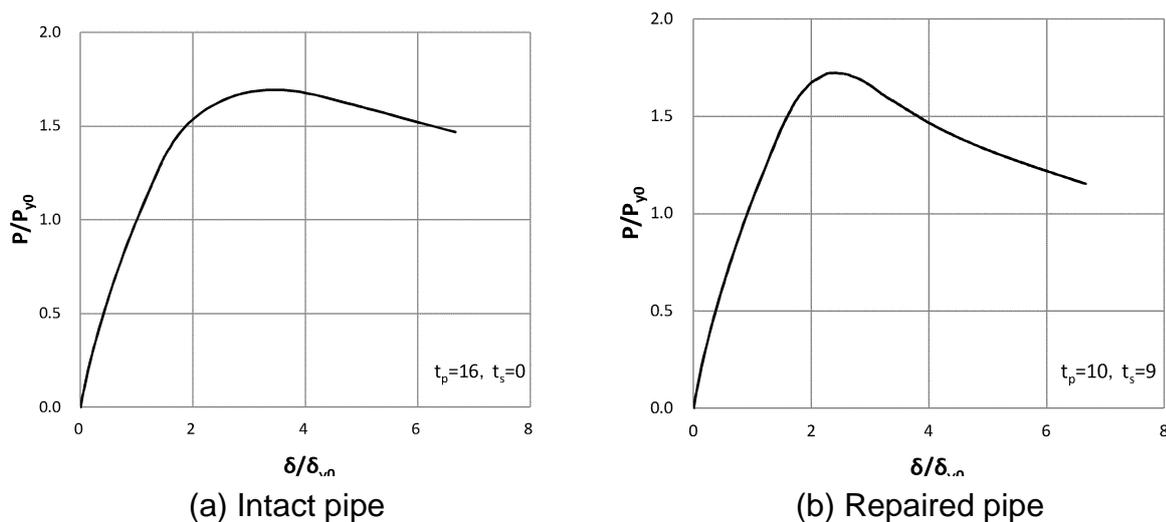

(a) Intact pipe   (b) Repaired pipe
Fig. 9 Load-displacement curves

Top of pile

Top of pile

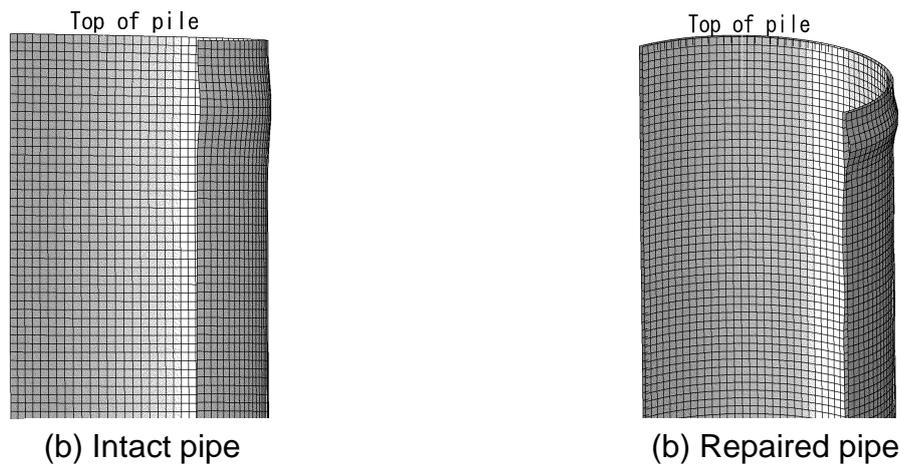(b) Intact pipe   (b) Repaired pipe

Fig. 10 Deformed shapes

3. EMPIRICAL FORMULA OF STEEL PATCH PLATE THICKNESS

3.1 Cantilever Model

Numerical analysis is performed by using a cantilever model to obtain an empirical formula to design a required thickness of patch plate. Fig. 11 is one of the steel pipe piles in the steel piled jetty of Fig. 1. When the upper concrete is subjected to horizontal force P, the inertial force during earthquake, Fig. 11 shows displacement profile and bending moment diagram of a pile. Fig. 12 shows the cantilever FE model extracted from the upper part of steel pipe pile shown in Fig. 11. First, the axial force N is applied at the loading end, and then, the pushover analysis is carried out by gradually increasing horizontal displacement δ. It is assumed that a reduced thickness of steel pipe is uniform in the model.
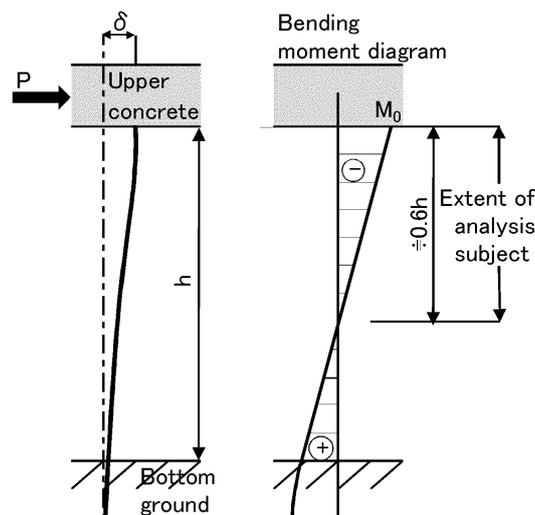
Fig. 11 Displacement and bending moment of
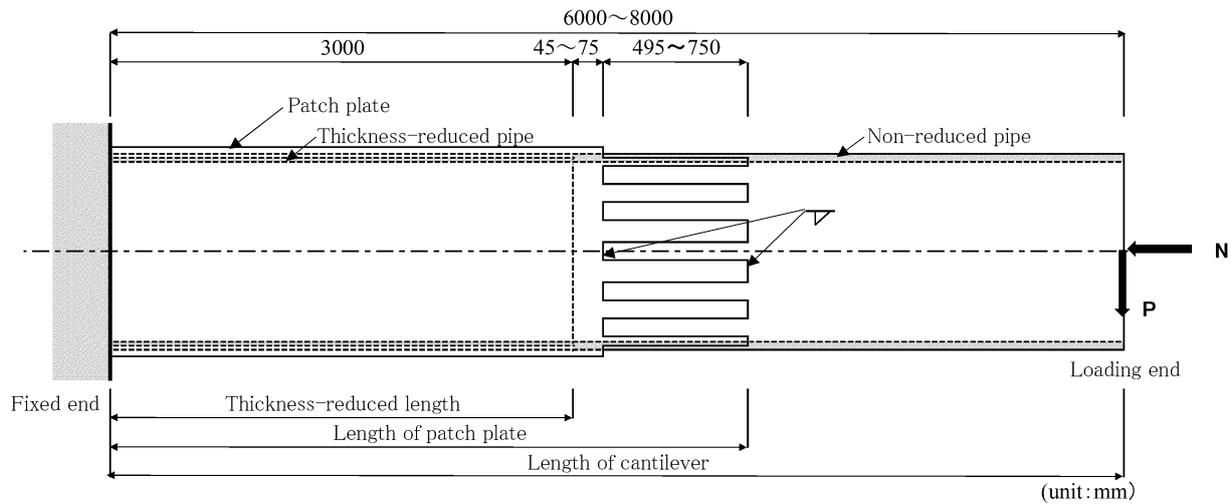pile subjected to horizontal force

Fig. 12 Analyzed model of thickness-reduced pipe repaired by patch plate

3.2 Pushover Analysis Results

Pipe diameters used in the analysis are 600 mm, 700 mm, 800 mm, and 900 mm. Original thickness of steel pipe is either 12 mm or 16 mm. Thickness reductions are assumed to be 6 mm, 8 mm, and 10 mm. Cantilever lengths considered are 6000 mm, 7500 mm, and 8000 mm. For steel piles, both SKK490 and SKK 400 are used. A ratio of the axial force to yielding axial force of an intact steel pipe N/N_y is considered to be 0%, 5%, 10%, 15% and 20%. The list of analytical cases is shown in Table 3. In total, 106 cases are analyzed. A required patch plate thickness is determined with an accuracy of 0.1 mm for each case.

Table 3 List of analytical cases

Diameter of pipe (mm)	Original thickness of pipe (mm)	Cantilever length (mm)	Yield stress of pipe (N/mm²)	Yield stress of patch plate (N/mm²)	Corrosion thickness (mm) Ratio of acting axial force to yielding axial force					Number of analytical cases
					0%	5%	10%	15%	20%	
600	16	6000	315	315	6,8,10	6,8,10	6,8,10	6,8,10	6,8,10	15
			235	235	8	-	8	-	8	3
			235	315	-	-	8	-	-	1
		7500	315	315	6,8	-	6,8	-	6,8	6
	12	6000	315	315	6	6	6	6	6	5
700	16	6000	315	315	6,8,10	6,8,10	6,8,10	6,8,10	6,8,10	15
			235	235	8	-	8	-	8	3
			235	315	-	-	8	-	-	1
		7500	315	315	6,8	-	6,8	-	6,8	6
	12	6000	315	315	6	6	6	6	6	5
800	16	6000	315	315	6,8,10	6,8,10	6,8,10	6,8,10	6,8,10	15
			235	235	8	-	6,8,10	-	8	5
			235	315	-	-	6,8,10	-	-	3
		8000	315	315	6,8	8	6,8	8	6,8	8
	12	6000	315	315	6	6	6	6	6	5
900	16	6000	315	315	6,8	6,8	6,8	6,8	6,8	10
Total number of cases										106

Fig. 13 Load-displacement curves

(c) Intact pipe   (b) Repaired pipe
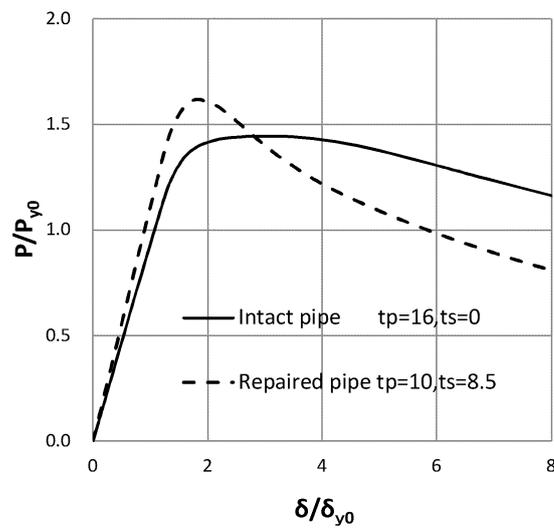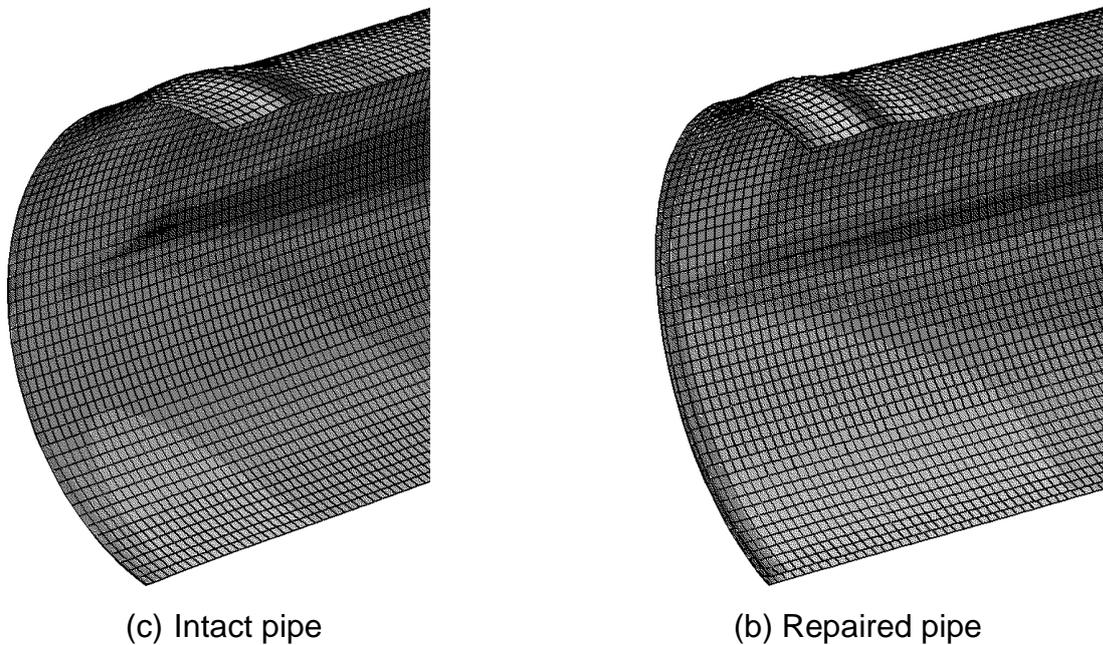
Fig. 14 Examples of deformed shapes

As an example of analysis results, load-displacement curves of cantilever models that are corresponding piles from the whole piled jetty model are shown in Fig. 13 for both intact pipe and repaired pipe. In Fig. 13, P and δ are normalized by the horizontal force P_{y0} and displacement of the loading point δ_{y0} when the initial yielding occurs at the fixed end. From analysis results, a required thickness of patch plate is 8.5 mm. In the case of a repaired pipe, it is found that load carrying capacity is suddenly reduced after local buckling. Deformed shapes of both intact and repaired pipes after local buckling are shown in Fig. 14.

3.3 Proposal of Empirical Formula

Required thicknesses of patch plate from 106 cases listed in Table 3 are plotted in Fig. 15. In Fig. 15, the parameter of the horizontal axis was selected by referring to the study on steel bridge piers (GE 1997). N/N_y is a ratio of axial force to yield axial force, λ_p is a slenderness ratio parameter of thickness-reduced steel pipe pile shown in Eq. (2), and R_{tp} is a radius thickness ratio parameter of the pile as shown in Eq. (3):

$$\lambda_p = \frac{1}{\pi}\sqrt{\frac{\sigma_{yp}}{E}}\frac{\ell}{r_p}, \tag{2}$$

$$R_{tp} = \frac{R_p}{t_p}\frac{\sigma_{yp}}{E}\sqrt{3(1-\mu^2)}, \tag{3}$$

where σ_{yp}, R_p, t_p, r_p, ℓ, E, and μ are yield stress of thickness-reduced pipe, radius of curvature on middle surface of the thickness-reduced pipe, thickness of the thickness-reduced pipe, radius of gyration, effective buckling length, Young's modulus and Poisson's ratio, respectively. The vertical axis (y-axis) is a parameter that represents a ratio of the patch plate thickness to the intact pipe thickness, where t_s, t_{p0}, σ_{ys}, σ_{y0} are patch plate thickness, intact pipe thickness, yield stress of patch plate and nominal yield stress of SKK490 (σ_{y0}=315N/mm^2), respectively.
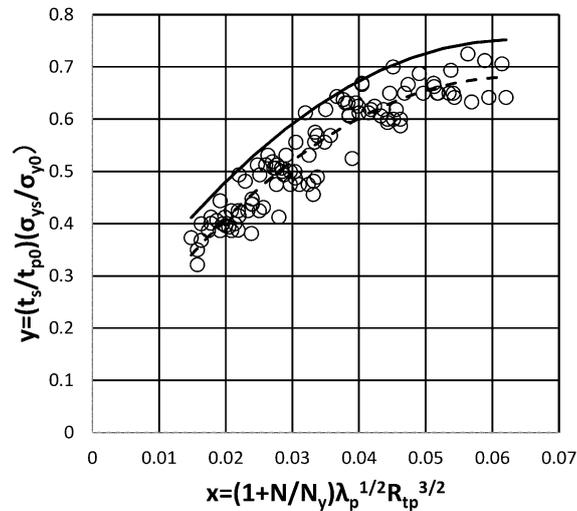
Fig. 15 Required thicknesses of patch plate from 106 analytical cases

In Fig. 15, a trend curve of average values obtained by a nonlinear least square method is shown as a dashed line, and a solid line is an upper limit curve of required thickness of patch plate representing average plus twice the standard deviation, which is expressed as follows:

$$y=-144x^2 + 18.3x + 0.172, \tag{4}$$

An applicable range of Eq. (4) is $0.015 \leqq x \leqq 0.060$, $0 \leqq N/N_y \leqq 0.2$, $0.07 \leqq R_{tp} \leqq 0.17$, $0.5 \leqq \lambda_p \leqq 0.9$, and $0.375 \leqq t_{cor}/t_{p0} \leqq 0.625$, where t_{cor} is thickness diminution.
    Let us apply Eq. (4) to the example of steel piled jetty shown in Fig. 1, where a thickness diminution of pile top is t_{cor}=6 mm, and the effective buckling length is the distance between the virtual ground and the upper concrete (ℓ =13.3m). Then, a required thickness of patch plate obtained from Eq. (4) is turned out to be t_{req}=9.1 mm. This value of thickness is the upper limit, and it is found that this value is almost the same thickness as a thickness of 9 mm obtained from the pushover analysis of the whole piled jetty model. Accordingly, it is verified that Eq. (4) can give an adequate thickness for patch plate.

4. VERIFICATION OF REQUIRED PATCH PLATE THICKNESS BY TIME HISTORY RESPONSE ANALYSIS

4.1 Time History Response Analysis Model
    To perform time history response analysis, the whole model of piled jetty as shown in Fig. 2 is modified to the model shown in Fig. 16. Features of this model and differences between this model and the pushover analysis model of Fig. 2 are listed below:
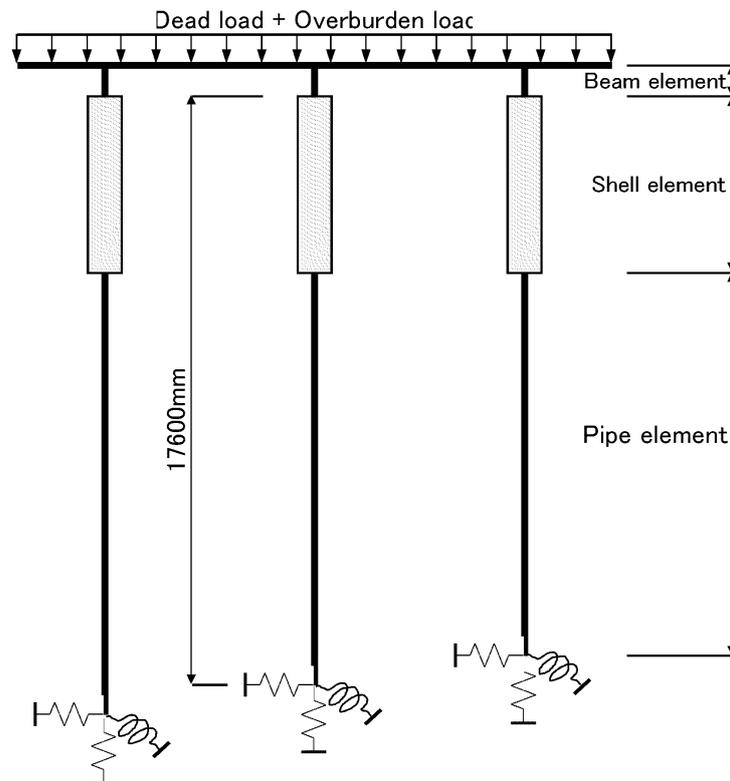
Fig. 16 Time history response analysis model

1) The points of spring supports are the maximum bending moment points in ground. Those points are obtained from the results of pushover analysis model of the steel piled jetty.
2) The constants of spring supports are based on the Japanese Specifications of Highway Bridges (Japan Road Association 2012).
3) Vertical loads of upper concrete a pile row are 86kN/m (dead load) and 65kN/m (over load). Dead load of pile is also considered. These loads are considered as gravity load.
4) Dynamic water pressure during earthquakes is not considered in this model.
5) The soil type is the second type in the specifications (Japan Road Association 2012). Its natural period of subsurface layer T_G is 0.2 sec $\leqq$ T_G< 0.6 sec.

4.2 Comparison between Pushover Model and Time History Response Model
To show the time history analysis model is equivalent to the pushover analysis model, the pushover analysis is performed on both models. Fig. 17 shows load-displacement curves from pushover analyses of both models. In Fig.17, the solid line shows the case of time history response model, and the dashed line shows the case of pushover model. It is found that the maximum horizontal force and the initial stiffness of the time history response model are in good agreement with those of the pushover model. The time history analysis model is found to show an equivalent horizontal force-displacement relationship to the pushover analysis model.
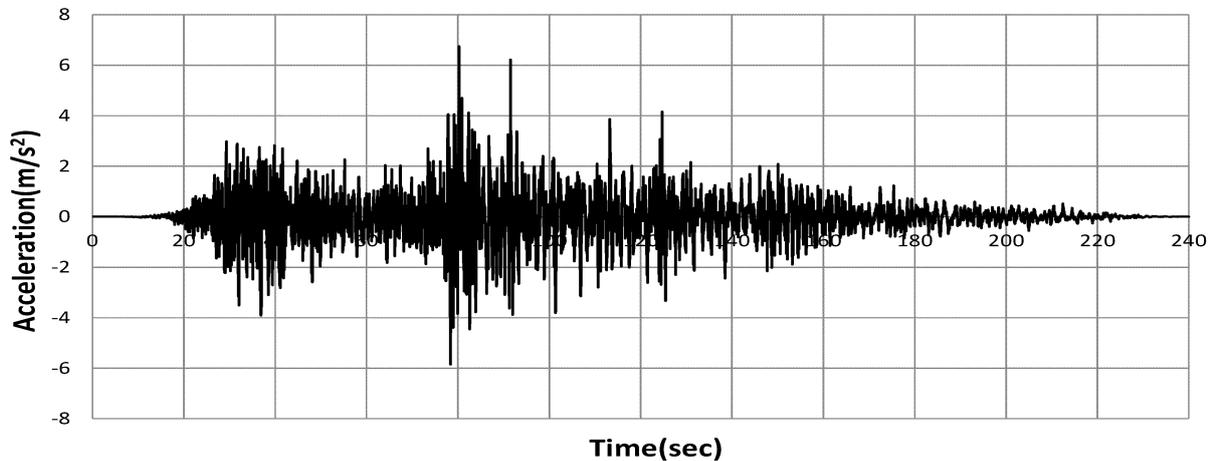

(d) Intact pipe   (b) Repaired pipe
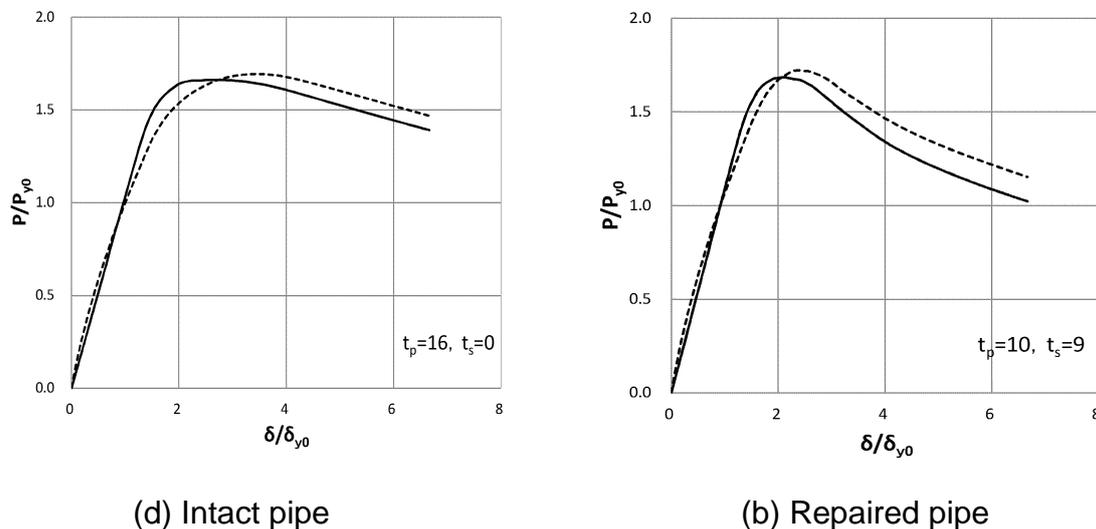
Fig. 17 Load-displacement curves

4.3 Input Ground Motions
Ground motion records from two major earthquakes, the 2011 off the Pacific coast of Tohoku earthquake and the 1995 Hyogo-ken Nanbu earthquake, are used. The 2011 off the Pacific coast of Tohoku earthquake is an inter-plate earthquake, and

one of recorded ground acceleration histories is shown in Fig. 18(a), named as Type I ground motion. The 1995 Hyogo-ken Nanbu earthquake is a near-field earthquake, and one of recorded ground acceleration histories is in Fig. 18(b), named as Type II ground motion.
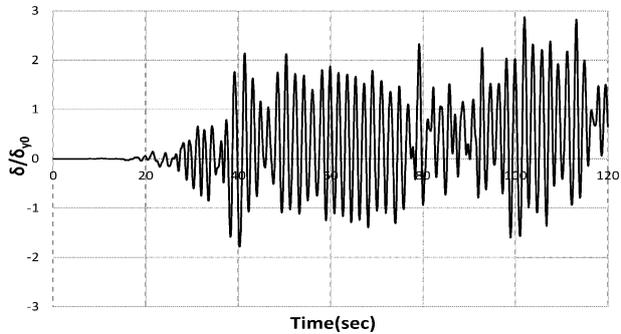

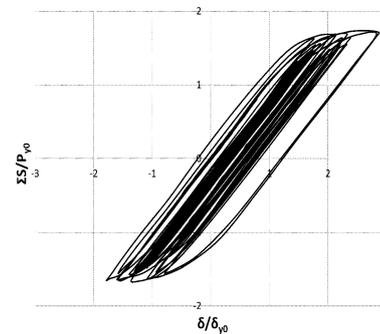
(a) Type I
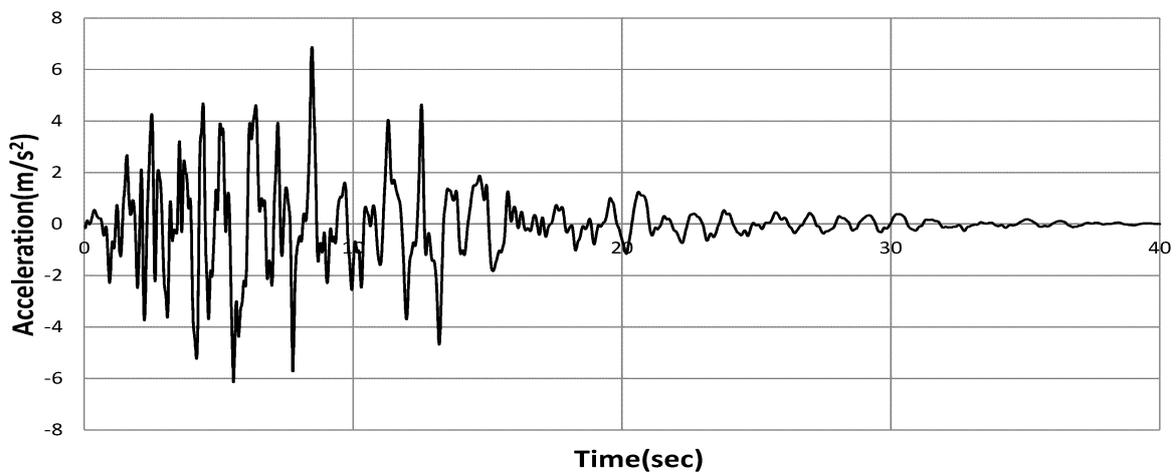
(b) Type II
Fig.18 Incident seismic wave

4.4 Response to Type I Ground Motion

Response displacements of intact, corroded, and repaired pipes during Type I ground motion are shown in Fig. 19, and displacement-horizontal force relationships for the three pipes are shown in Fig. 20, where ΣS is the sum of horizontal force at the pile bottom. From these figures, behavior of the repaired pipe is similar to that of the intact

pipe although the load carrying capacity of the corroded pipe is considerably reduced from the intact pipe.
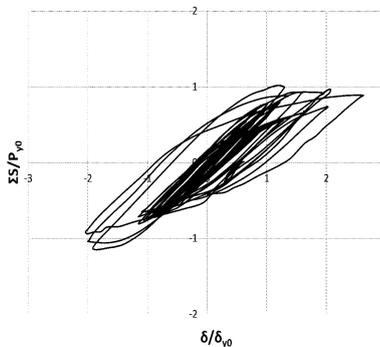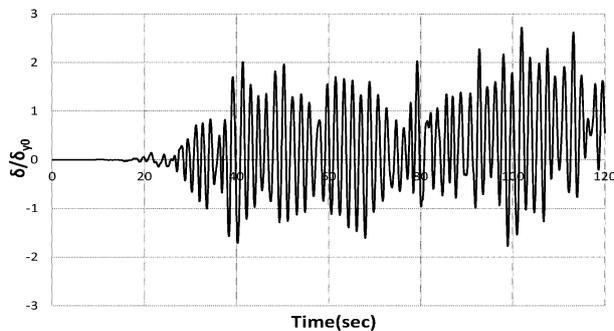

(a) Intact pipe
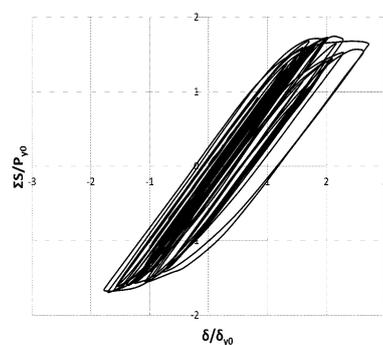

(a) Intact pipe
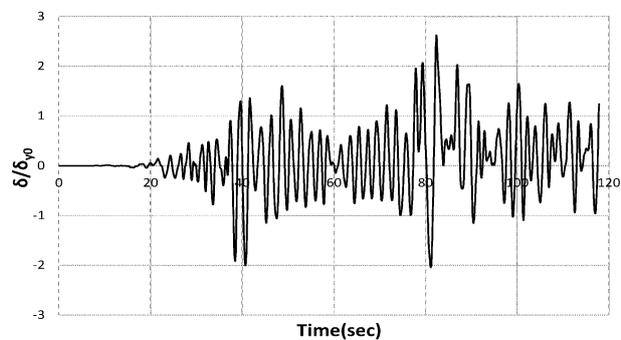
(b) Corroded pipe

(b) Corroded pipe

(c) Repaired pipe
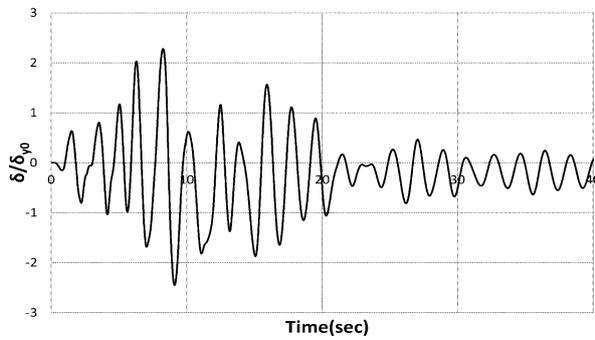Fig. 19 Response Displacement

(c) Repaired pipe
Fig. 20 Response displacement-
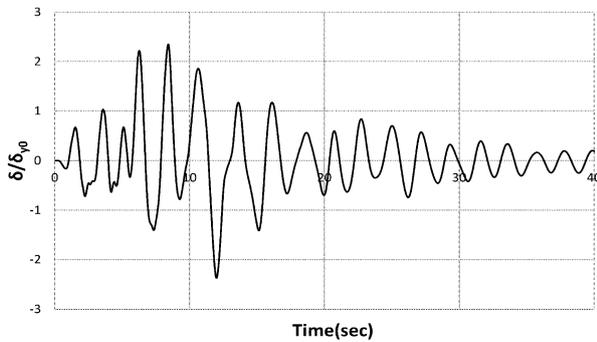base shear force relation

4.5 Response to Type II Ground Motion

Response displacements during Type II ground motion are shown in Fig. 21, and horizontal displacement-force relationships are shown in Fig. 22. It can be seen that behavior of the repaired pipe is similar to that of the intact pipe although the load-
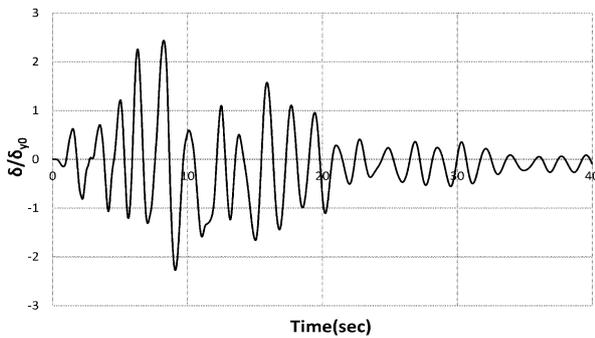
carrying capacity of the corroded pipe is considerably reduced from the intact pipe. It is found from these results that the repaired pipe with a patch plate thickness obtained by Eq. (4) shows the same level of seismic performance as that of the intact pipe.
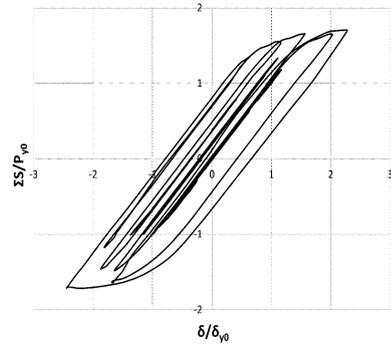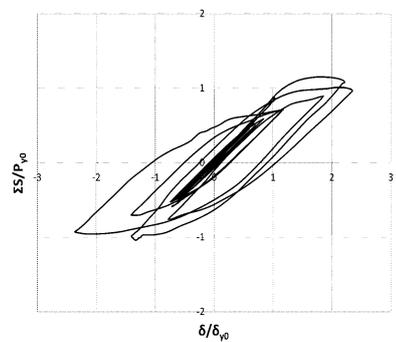
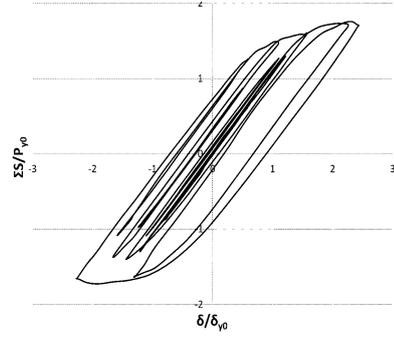

(a) Intact pipe

(a) Intact pipe

(b) Corroded pipe

(b) Corroded pipe

(c) Repaired pipe
Fig. 21 Response Displacement

(c) Repaired pipe
Fig. 22 Response displacement-
base shear force relation

5. CONCLUSIONS

The seismic performance of a repaired steel piled jetty is examined in this study. First, pushover analyses of a steel piled jetty are performed for intact, corroded, and

repaired pipes. From the results of the analyses, required thicknesses of patch plate are obtained. Then, an empirical formula on a required thickness of patch plate is proposed based on results obtained by using cantilever pipe pile models with different structural parameters. At last, validity of the empirical formula is confirmed by a time history response analysis of the steel piled jetty. Major conclusions are described as follows.

1) An empirical formula for a required patch plate thickness is proposed from an examination of results obtained by the pushover analyses of cantilever models. The proposed formula gives almost the same thickness as that obtained by the pushover analysis of the whole steel piled jetty model.

2) Time history response analysis confirmed that a repaired pipe with the patch plate thickness given by the proposed formula has the same seismic performance as the intact pipe.

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