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SEISMIC FRAGILITY ANALYSIS FOR SHEET PILE WHARVES - CASE STUDY OF THE HUALIEN HARBOR IN TAIWAN

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ABSTRACT

The seismic fragility curves represent the conditional probabilities that the structural damage meets or exceeds the specified damage states at various levels of the ground motion parameters, such as peak ground acceleration (PGA). In this study, the seismic fragility analysis for the sheet pile wharves of the Hualien Harbor in Taiwan was performed. The finite element analysis software PLAXIS was adopted for the nonlinear dynamic analysis. The time histories of several representative earthquake events that actually occurred in Taiwan, including the 1999 Chi-Chi Earthquake, were scaled to various PGA levels as the input motions. Then the seismic responses of the sheet pile wharves subjected to these earthquakes of different intensities were obtained. It is assumed that the maximum residual displacement at the top of the sheet pile wall is lognormal distributed. Thus, the conditional exceedance probabilities of each specified damage state at different levels of PGA were estimated according to the displacement threshold value of each damage state, and the fragility curves were deduced. Moreover, these fragility curves were parameterized assuming they can be well approximated by the lognormal cumulative probability function, which is important for the rapid estimation of earthquake loss.

INTRODUCTION

Taiwan is located on the active seismic belt around the Pacific Ocean so that the earthquakes have continuously been a major threat. On September 21, 1999, the Chi-Chi Earthquake attacked central Taiwan, caused serious casualties and property losses and greatly impacted the society. Therefore, since then the government and the academies of Taiwan have devoted to the seismic disaster prevention and reduction projects and researches against future earthquakes.

In general, risk can be defined by occurrence probability of a seismic event, exposure of people and property to the event, and consequences of that exposure. Therefor, by integrating the knowledge of the geophysics, civil engineering, and socio-economics, the earthquake loss estimation methodology has been proposed, such as the HAZUS 99 (FEMA, 1999) in the United States. In Taiwan, the National Center for Research on Earthquake Engineering (NCREE) has established the prototype of the "Taiwan Earthquake Loss Estimation System" (TELES) (Yeh *et al.*, 2006), in which the modules for the seismic hazard analysis, the damage evaluation of structures, and the estimation of direct socio-economic losses, have been well developed. The framework of TELES is shown in Fig. 1.

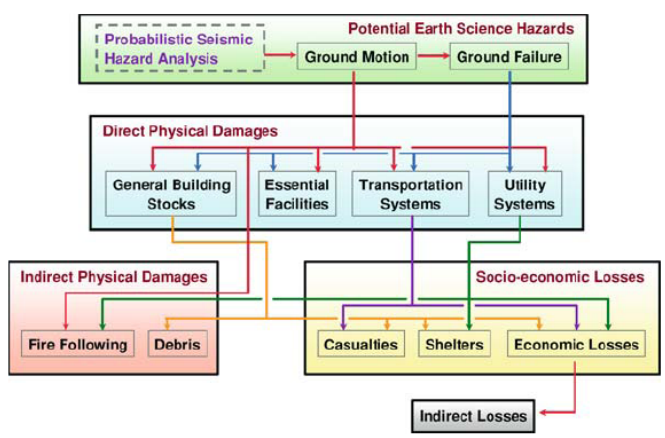


Fig. 1. Framework of Taiwan Earthquake Loss Estimation System(TELES) (Yeh et al.,2006).

Taiwan is also an island surrounded by the ocean and therefore the harbors are important for the domestic and international transportation. The harbor facilities would be damaged under strong earthquakes, which not only leads to safety concerns but also influences the normal operation of the harbor. Consequently, it is necessary to estimate the possible loss due to the structural damage of the harbor facilities subjected to strong earthquakes in advance. For this reason, the NCREE and the Harbor and Marine Technology Center (HMTC) in Taiwan have cooperated since 2007 to execute the project "Seismic Hazard and Seismic Capacity Evaluation of Port Structures in Harbor Areas" (Lai *et al.*, 2008; Hsieh *et al.*, 2009), which aims at developing a new module that can be incorporated into TELES to assess the possible loss of a port system during earthquakes. The scope of project includes: (1) evaluating the earthquake potential and seismic hazards for the specified harbor areas, (2) evaluating the seismic capacity of important port structures in the selected harbor area, and (3) conducting the earthquake loss estimation for the specified harbor area during scenario earthquakes.

In evaluating the possible seismic damages of a structure, the fragility curve is often introduced. It represents the conditional probabilities that the structural damage meets or exceeds specified damage states under various levels of seismic excitation, which usually in terms of peak ground acceleration (PGA), spectral acceleration (S_a), or spectral displacement (S_d). Since the damage state can not be easily defined by a specific parameter, it is usually described as slight, moderate, extensive, and complete damages. The fragility curves of these damage states are as demonstrated in Fig. 2. When PGA=a, the probability that a structure is in the damage state d_s can be expressed as Eq. (1), the difference of adjacent fragility curves:

$$\begin{aligned} & P[DS = d_s \mid PGA = a] \\ & = P[DS \geq d_s \mid PGA = a] - P[DS \geq d_{s+1} \mid PGA = a] \end{aligned} \quad (1)$$

Each type of structures has its individual fragility curve that exhibits its seismic vulnerability. Generally the fragility curves can be derived using analytical or numerical methods, from empirical data obtained from past earthquakes, or from expert opinions. The fragility curves can be applied to the rapid evaluation of structural damage, which is essential to the earthquake loss estimation system. Therefore, the fragility analysis of port structures is one of the important jobs in developing the module for port system in TELES.

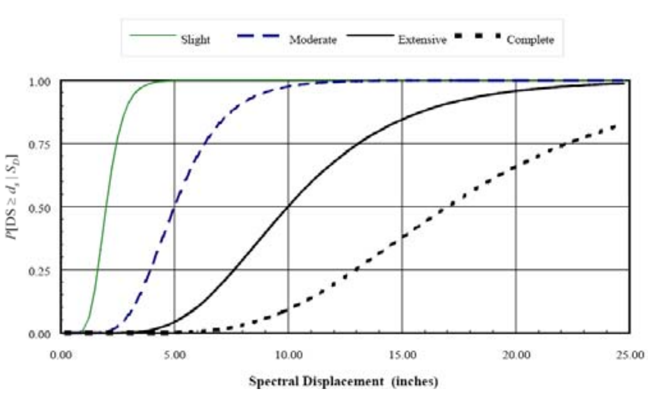


Fig. 2. Example fragility curves for slight, moderate, extensive and complete damage (FEMA,1999).

In this paper, the seismic fragility analysis for sheet pile wharves, which are common in harbors of Taiwan, are presented. Two sheet pile wharves of the Hualien Harbor in Taiwan are selected for case study. Since the empirical data of earthquake-damaged port structures in Taiwan is quite limited, and the reliability of expert opinions are difficult to verify, the numerical method is used for the fragility analysis in this study. The finite element (FE) analysis software PLAXIS 8.2 (Brinkgreve, 2002) is adopted to generate the FE models of these two sheet pile wharves. The time histories of actual earthquake events are used as the input motions and the seismic analyses are carried out by using these models to verify their validity. Finally, the procedures of the seismic fragility analysis for sheet pile wharves are proposed, and the FE models established are introduced to perform the fragility analysis in order to deduce the fragility curves of sheet pile wharves for the earthquake loss estimation of harbor areas.

SEISMIC ANALYSIS OF SHEET PILE WHARF

Analysis Method

A sheet pile wharf is composed of interlocking sheet piles, tie-rods, and anchors, as shown in Fig. 3. The sheet pile wall is supported at the upper part by anchors and the lower part by embedment in competent soil (PIANC, 2001). When the earthquake occurs, the seismic response of the sheet pile wharf will be influenced by the interaction of the sheet pile wall and the soil body in front of and behind the wall. Therefore, while performing the seismic analysis of the sheet pile wharf, it is necessary to use the model that can take the soil-structure interaction into consideration for the real assessment of the seismic response under the excitation of earthquakes.

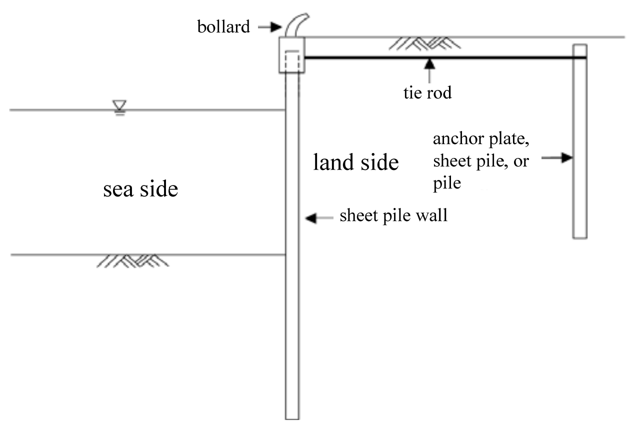


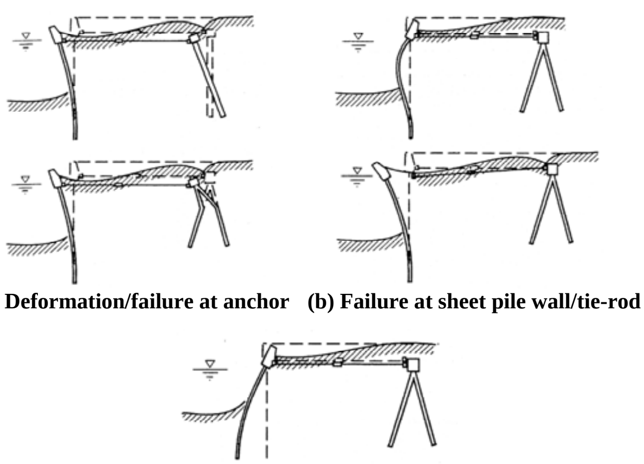
Fig. 3. Cross section of a typical sheet pile wharf.

Analysis methods for the seismic response of the retaining structure of the wharves generally include the pseudo-static analysis, which is based on the conventional force-balance approach, the simplified dynamic analysis, which idealizes a structure by a sliding rigid block, and the rigorous dynamic analysis, which is based on soil-structure interaction and generally uses the finite element method (FEM) or the finite difference method (FDM) (PIANC, 2001). In the rigorous dynamic analysis, the variability of ground motions can be represented by using a series of the time histories of actual earthquakes as the input motions. The non-linearity of the materials and the interaction between soil and structure can be well-considered by introducing reasonable models. Moreover, fairly comprehensive analysis results can be obtained, including the failure modes of the soil-structure system and the extent of the displacement, stress, or strain states, which can be used for the determination of the damage state of the analyzed wharf according to corresponding damage criteria.

Therefore, the rigorous dynamic analysis is adopted for the fragility analysis in this study. The FE analysis software PLAXIS 8.2 (Brinkgreve, 2002) is used since it is originally developed for geotechnical analysis. Also, FEM can well model the structural members in a sheet pile wharf such as the sheet pile, the tie-rod, and the anchor, and can therefore perform the soil-structure analysis to an acceptable precision. Besides, it has a high execution efficiency, which is important for the massive case analyses in deriving the fragility curves.

Failure Modes and Damage Criteria of Sheet Pile Wharf

According to the case histories, the typical failure modes of sheet pile wharves during earthquakes can be induced (PIANC, 2001), including the deformation or failure at the structural members such as the anchor, the sheet pile wall and the tie-rod, as well as the failure at embedment, as shown in Fig 4.



(a) Deformation/failure at anchor **(b) Failure at sheet pile wall/tie-rod**

(c) Failure at embedment

Fig. 4. Deformation/failure modes of sheet pile wharf (PIANC, 2001).

The possible reasons for these failure modes are:

1. The dynamic earth pressure and water pressure cause the stress state of the structural members exceed their design strength, leading to large deformations or even failure.
2. The deformation of the sheet pile wall toward the sea side causes the active failure of the soil body behind the wall and the passive failure in front of the wall, leading to the settlement of the apron. In addition, soil liquefaction can also induce the failure of the embedment.

Considering the failure modes just mentioned, the damage criteria for sheet pile wharves are given in Table 1. Table 1(a) was proposed by Uwabe (1983) based on empirical data of earthquake damage, and the parameter for specifying damage criteria is the maximum residual displacement at the top of the sheet pile wall. The definitions of the damage states are:

- Degree 0 - No damage;
- Degree I - Negligible damage to the wall itself;
- Degree II - Noticeable damage to the wall itself;
- Degree III- General shape of anchored sheet pile preserved, but significant damaged;
- Degree IV- Complete destruction, no recognizable shape of wall remaining.

Table 1(b) was proposed by PIANC (2001) based on the serviceability of the wharf. The parameters for specifying damage criteria are mainly the stress states at the structural members. The definitions of the damage states are:

- Degree I - Minor or no structural damage; little or no loss of serviceability.
- Degree II - Controlled structural damage; short-term loss of serviceability.
- Degree III- Extensive structural damage in near collapse; long-term or complete loss of serviceability
- Degree IV- Complete structural damage; complete loss of serviceability.

Table 1. Damage criteria for sheet pile wharves

(a) According to Ukawa (1983)

Level of damage	Maximum residual displacement at sheet pile top (cm)
Degree 0	0
Degree I	< 30
Degree II	30~100
Degree III	100~200
Degree IV	>200

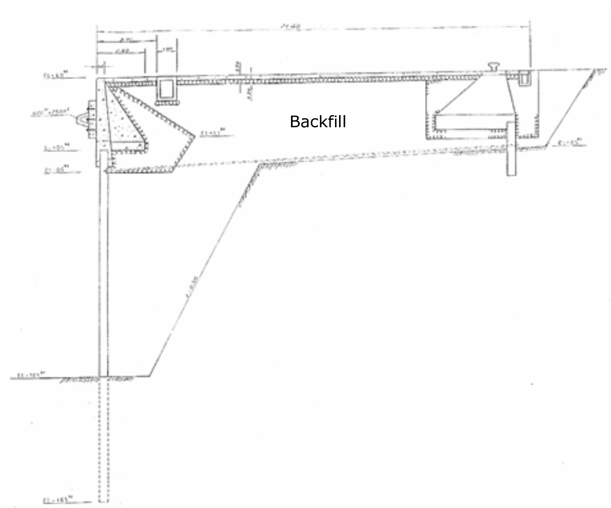
(b) According to PIANC (2001)

Level of damage	Sheet pile wall		Tie-rod	Anchor
	Above mudline	Below mudline		
Deg. I	Elastic	Elastic	Elastic	Elastic
Deg. II	Plastic (less than ductility factor)	Elastic	Elastic	Elastic
Deg. III	Plastic (less than ductility factor)	Plastic (less than ductility factor)	Plastic (less than ductility factor)	Plastic (less than ductility factor)
Deg. IV	Plastic (beyond ductility factor)	Plastic (beyond ductility factor)	Plastic (beyond ductility factor)	Plastic (beyond ductility factor)

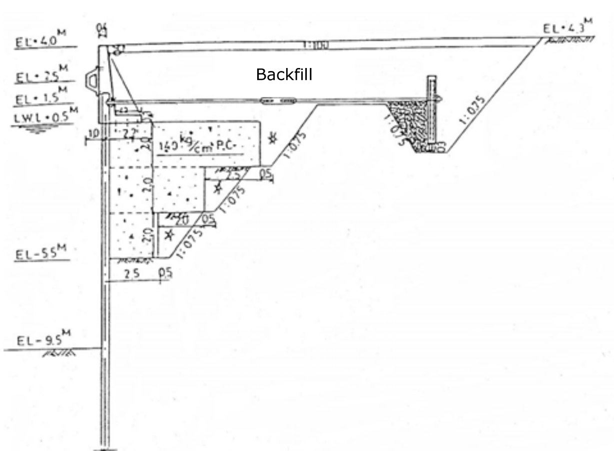
The definitions of damage states proposed by Uwabe (1983) and PIANC (2001) are generally correspondent, except the degree I of the latter covers degrees 0 and I of the former. Therefore, the damage criteria in Table 1(a) and Table 1(b) are comprehensively referred to in the following seismic analysis and fragility analysis for the judgment of the damage state.

Cases for Analysis

The sheet pile wharves in the Hualien Harbor in Taiwan include Wharf No. 4, No. 5, No. 6, No.8, and No. 9, which are all composed of the sheet pile wall, tie-rods, and RC anchor plates. Among these wharves, No. 4, No. 5, No. 6, No.8 are similar in the cross section and can be regarded as the same type, taking No. 8 as representative, the cross section as shown in Fig. 5(a). As for Wharf No. 9, the cross section is more particular since its retaining structure consists of not only the sheep pile wall, but also the plain concrete block installed behind the wall, serving as the additional gravity retaining wall, as shown in Fig. 5(b).



(a) Wharf No. 8 of Hualien Habor



(b) Wharf No. 9 of Hualien Habor

Fig. 5. Cross-sections of cases for study

Input Motions

According to the suggestion of PIANC (2001), two levels of earthquake motions are typically used as design reference motions in performance-based design:

- Level 1 (L1)- The level of earthquake motions that are likely to occur during the life-span of the structure, typically defined as motion with a probability of exceedance of 50% during the life-span of the structure.
- Level 2 (L2)- The level of earthquake motions associated with infrequent rare events that involve very string ground shaking, typically defined as motion with a probability of exceedance of 10% during the life-span of the structure.

Generally the life-span of port structures is 50 years, and thus the return periods for L1 and L2 motions are 75 years and 475 years, respectively. Considering the importance of the port structures in the Hualien Harbor, the allowable damage level is degree I (serviceable) for L1 motions and degree II (repairable) for L2 motions. The input motions used in this section is based on the time history recorded at the Hualien Weather Station (seismic station HWA019) during the March 31, 2002, Hualien offshore earthquake (M_L 6.8). A 50-second time history that contains over 95% of the total energy is extracted from the original record and is scaled according to the results of a recent seismic hazard analysis of the Hualien Harbor area (Hsieh *et al.*, 2009). That is, the L1 motion has a PGA of 0.379g, and L2 motion has a PGA of 0.557g.

Table 2. Representative soil profile at the site

Layer	Description	Thickness (m)	Density (t/m^3)	V_P (m/s)	V_S (m/s)	Damping ratio ξ	Poisson's ratio ν
I	Surface soil, boulders	9.0	2.04	1658	500	0.02	0.45
II	Boulders	10.0	2.04	1990	600	0.02	0.45
III	Rock	-	2.04	2322	700	0.02	0.45

FE Model of Sheet Pile Wharf

Site-Specific Ground Response Analysis. First, the SHAKE 91 code (Idriss and Sun, 1992), which has been widely used for the ground response analysis, is adopted to perform the deconvolution analysis using the actual earthquake time history recorded at the free-field surface at this site as input motion to obtain the base motion. Based on available soil boring data, the depth of the base rock is around 10~20m in the Hualien Harbor, and above the base rock the strata are mainly composed of boulders. Moreover, the seismic survey data show that the P-wave velocity at the site is between 1650m/s and 2350m/s (HMTC, 1996). Integrating all these data, the representative soil profile and the conservative soil parameters are accordingly determined for the initial setting of the SHAKE analysis, as listed in Table 2.

The free-field surface motion for the deconvolution analysis is the time history of the March 31, 2002, Hualien offshore earthquake. For the case that the PGA scaled to 0.2g, the calculated zero period acceleration (ZPA) at the base rock is 0.173g, and therefore the amplification effect in the Hualien Harbor area is not significant. In addition, the strain-compatible soil properties obtained during the iteration processes in SHAKE analysis will be used as the equivalent-linear soil parameters for the FE ground model.

Table 3. Soil parameters for the non-linear seismic analysis

Soil type	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	E (kN/m^2)	ξ	ν	c (kPa)	ϕ (deg)
Block stones	16.0	20.0	1.0×10^6	0.054	0.45	5.0	40
Backfill grade	16.0	20.0	3.0×10^5	0.054	0.45	5.0	35
Original strata	16.0	20.0	1.1×10^6	0.054	0.45	10.0	45

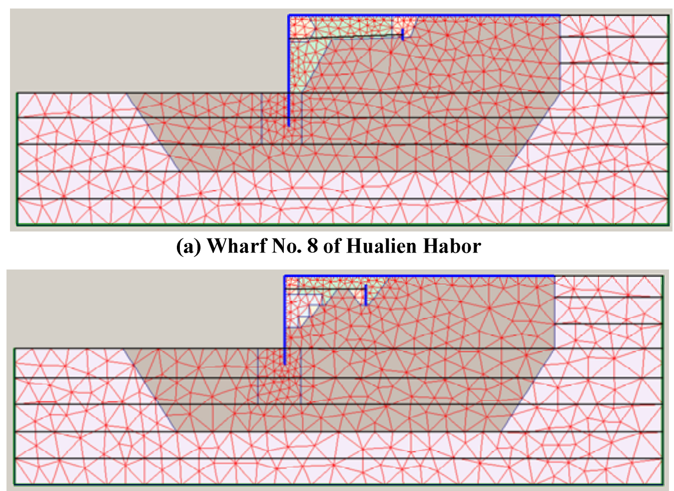
FE Model of the Ground. Since the harbor is a line-shaped structure and the movement toward the sea side is more critical for the sheet pile wall during earthquakes, the plane-strain analysis was performed for the seismic response of the sheet pile harbor. The ground model was generated by the 6-node plane strain triangular solid element. In the seismic analysis, the soil nonlinearity must be properly taken into consideration. As mentioned in the previous section, the equivalent-linear strain-compatible soil parameters obtained in SHAKE analysis were used for the ground model, as listed in Table 3. The Mohr-Coulomb criterion was adopted for the modeling of the plastic failure of the soil. The Rayleigh damping model provided by the PLAXIS code was used for the simulation of hysteretic soil damping through appropriate parameter settings (Ko *et al.*, 2009), approximating the inherent energy dissipation mechanisms of the soil material. Rigid link was applied to tie together the two nodes at the both ends of each layer, which allows for local disturbances in the near field due to the topographic effects and the existence of the structures, but forces the ground to behave globally as a 1D soil column. In order to reduce the undesirable effect of fictitious reflections, the absorbent boundary was imposed at both edges of the ground model. In the seismic analysis, the free-field surface motions were directly input at the bottom of the ground model. Since the amplification effect at this site is not significant according to the ground response analysis, and since the absorbent boundary will suppress the amplification effect, the ground as a whole will experience a motion similar to the free-field surface motion either in intensity or in spectral characteristics, leading to a more conservative result, and still allowing for the local disturbances in the near field.

Table 4. Parameters of structural members of sheet pile wharf

Structure type	Self weight (kN/m/m)	EA (kN/m)	EI (kN-m^2/m)	Yielding moment (kN-m/m)	Yielding tension (kN)
Sheet pile	1.138	3.0×10^6	6.0×10^4	581.5	-
Anchor pale	11.25	1.1×10^7	2.2×10^5	200.0	-
Tie-rod	-	8.4×10^5	-	-	1004.5

FE Model of Structural Members. The sheet pile wall and the RC anchor plate were modeled by the plate element, while the tie-rod was modeled by the node-to-node anchor of PLAXIS, which is intrinsically an axial force member. The nonlinear behavior of the structural members was simulated by elastic-plastic model with the yielding moment of the plate element and the yielding tension of the axial force member specified. Considering the coupling between the moment and the axial force of the plate element, its yielding moment will be reduced to an appropriate degree depending on the actual axial force. The material and section properties were specified according to the design conditions, as listed in Table 4.

The FE model of the sheet pile wharves is shown in Fig. 6.



(a) Wharf No. 8 of Hualien Habor

(b) Wharf No. 9 of Hualien Habor

Fig. 6. FE model of sheet pile wharves

Analysis Results

Wharf No. 8 under L1 Motion (PGA=0.379g). The deformed mesh, the moment distribution along the sheet pile wall, the tension of the tie-rod, and the moment distribution along the anchor plate are shown in Fig 7. The maximum residual displacement at the top of the sheet pile wall is 62.7 cm; the maximum moment in the sheet pile wall is 462.4 kN-m/m, occurring above the mud line. The tension of the tie-rod is 328.2 kN/m. The maximum moment in the anchor plate is 112.1 kN-m/m, occurring at the end of the tie-rod. Although all the structural members do not yield, the residual displacement at the top of the sheet pile has exceeded 30cm. Consequently, the damage level of Wharf No. 8 of the Hualien Harbor is at degree II in this case according to Table 1.

Wharf No. 8 under L2 Motion (PGA=0.557g). The deformed mesh, the moment distribution along the sheet pile wall, the tension of the tie-rod, and the moment distribution along the anchor plate are shown in Fig 8. The maximum residual displacement at the top of the sheet pile wall is 101.6 cm; the maximum moment in the sheet pile wall is 547.2 kN-m/m and has exceeded the yielding moment, occurring above the mud line. The tension of the tie-rod is 263.6 kN/m. The maximum moment in the anchor plate is 99.2 kN-m/m, occurring at the end of the tie-rod. The sheet pile wall below the mud line does not yield. The tie-rod and the anchor plate do not yield also, and their stress states are even less severe than the case under L1 motion. However, the residual displacement at the top of the sheet pile wall is just beyond 100cm. Hence, the damage level of Wharf No. 8 is between degree II and degree III in this case according to Table 1.

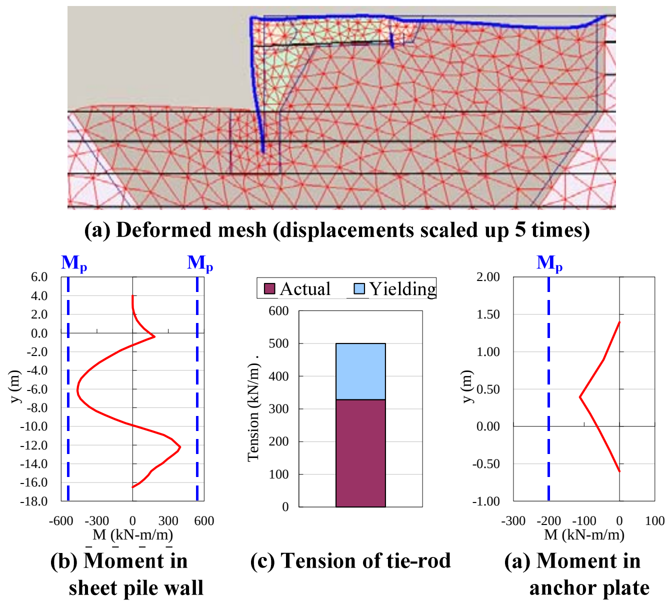


Fig. 7. Seismic response of Wharf No. 8 of Hualien Harbor (L1 motion, PGA=0.379g)

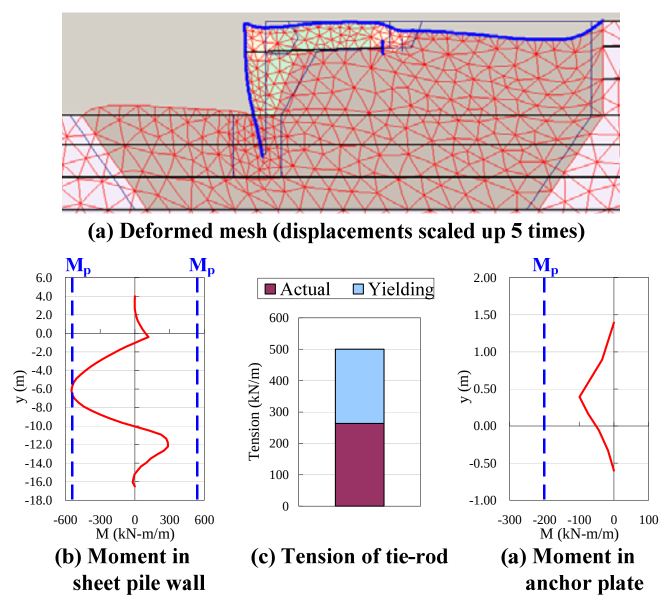


Fig. 8. Seismic response of Wharf No. 8 of Hualien Harbor (L2 motion, PGA=0.557g)

<u>Wharf No. 9 under L1 Motion (PGA=0.379g)</u>. The deformed mesh, the moment distribution along the sheet pile wall, the tension of the tie-rod, and the moment distribution along the anchor plate are shown in Fig 9. The maximum residual displacement at the top of the sheet pile wall is 63.6 cm; the maximum moment in the sheet pile wall is 506.4 kN-m/m and has been beyond the yielding moment, occurring above the mud line, at the bottom of the concrete block. In addition, the maximum moment in the sheet pile wall below the mud line is 475.5 kN-m/m and is close to the yielding moment. The tension of the tie-rod is 86.4 kN/m, and the maximum moment in the anchor plate is 23.2 kN-m/m, occurring at the end of the tie-rod, both far from yielding. The installation of the concrete block influences the deformation mode of the sheet pile wall, leading to the plastic hinge at the contact of the wall and the bottom of the block and enlarging the sheet pile moment below the mud line as well. Although the block acts as a gravity retaining wall and makes the anchor facilities in a mild stress state, yet in other words, it means the anchoring is not well-functioned. According to Table 1, the damage level of Wharf No. 9 of the Hualien Harbor is at degree II in this case.

<u>Wharf No. 9 under L2 Motion (PGA=0.557g)</u>. The deformed mesh, the moment distribution along the sheet pile wall, the tension of the tie-rod, and the moment distribution along the anchor plate are shown in Fig 10. The maximum residual displacement at the top of the sheet pile wall is 101.2 cm; the maximum moment in the sheet pile wall is 502.5 kN-m/m, beyond the yielding moment, occurring above the mud line. The maximum moment in the sheet pile wall below the mud line is 470.0 kN-m/m, also close to the yielding moment. The tension of the tie-rod is 84.1 kN/m, and the maximum moment in the anchor plate is 32.8 kN-m/m, both far from yielding. Accordingly, the damage level of Wharf No. 9 of the Hualien Harbor is between degree II and degree III in this case.

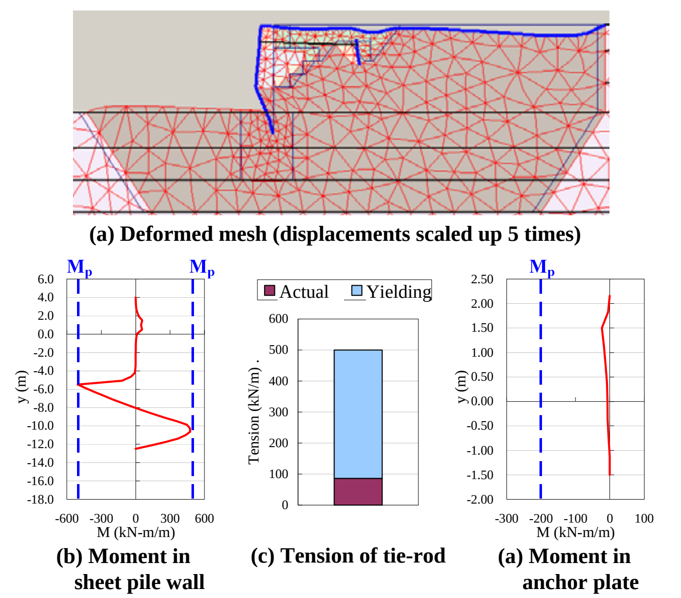


Fig. 9. Seismic response of Wharf No. 9 of Hualien Harbor (L1 motion, PGA=0.379g)

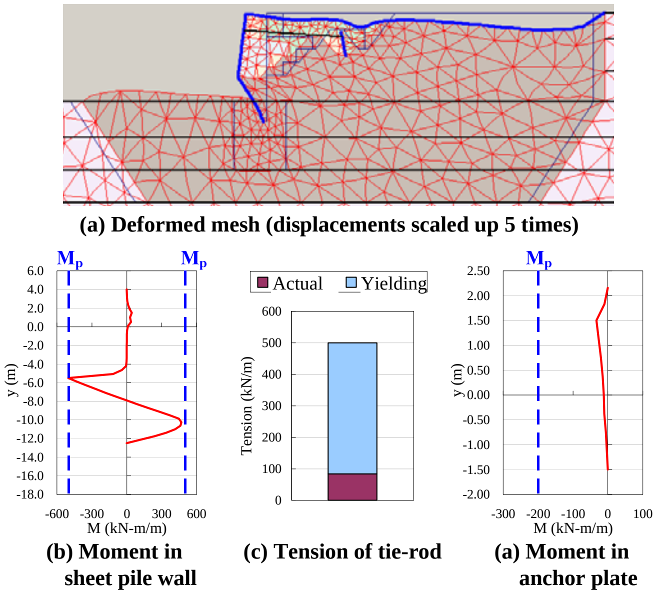


Fig. 10. Seismic response of Wharf No. 9 of Hualien Harbor (L2 motion, PGA=0.557g)

Discussions. From the analysis results above, we know that the damage levels of Wharf No. 8 and Wharf No. 9 of the Hualien Harbor are in degree II, short-term loss of serviceability yet repairable, under the excitation of L1 motions, and are between degree II and degree II, possible extensive structural damage and long-term loss of serviceability, under L2 motions. For of the port structures in the Hualien Harbor, the allowable damage level is in degree I for L1 motions and degree II for L2 motions. Therefore, the seismic capacity of Wharf No. 8 and Wharf No. 9 is somewhat insufficient with respect to the seismic hazard analysis of the Hualien Harbor area based on most up-to-date earthquake data. However, the design PGA corresponding to 475-year return period (L2 motion) is 0.33g in Hualien according to the current design code for port structures in Taiwan. Thus, the seismic capacity meets the design requirement. On the other hand, based on the assumption that these two wharves were well designed, the analysis model used in this study is capable of giving reasonable assessment of the seismic response of the sheet pile wharves. Moreover, the tie-rod and the anchor plate in each case are not close to yielding, even in the Wharf No. 8 case in which there is no concrete block installed. This is probably due to the length of the anchor plate is insufficient so that the soil reaction is not enough to anchor it adequately, causing the strength of the tie-rod not well-developed.

FRAGILITY ANALYSIS OF SHEET PILE WHARF

Analysis Method and Analysis Procedures

The seismic response of the sheet pile wharf will be dominated not only by the strong motion characteristics, but also by the interaction of the sheet pile wall and the soil body. Therefore, while performing the seismic fragility analysis of the sheet pile wharf, the key is to use the analysis model that can properly take the soil-structure interaction into account in evaluating the seismic response for the reasonable estimation of the possible damage state of the wharf under various levels of excitations of the earthquakes.

In the section of the seismic analysis of the pile sheet wharf, the dynamic analysis using FEM was performed. The time histories of actual earthquakes were used as the input motions to represent the variability of earthquakes. The non-linearity of the materials and the soil-structure interaction were well-modeled. The failure modes of the wharf, the displacements, and the stress states were obtained for the clear determination of the damage state based on corresponding damage criteria. Hence, although the dynamic FE analysis is time-consuming, it is adopted for the fragility analysis for sheet pile wharves in this study after the optimization of the coarseness of the mesh and the size of the model to enhance the analysis efficiency.

For the inclusion of the site effect and the variability of the structural capacity and damage state in the fragility analysis, it is essential to establish the model of each type of the wharf in each important harbor area and to perform numerous seismic analysis under excitations with various levels of the ground motion parameters (PGA is adopted in this study) for the further estimation of the conditional probability.

The procedures proposed in this study for the establishment of the fragility curves of the sheet pile wharf are as follows:

1. Generate the FE model of a typical sheet pile wharf.
2. Choose several sets of the free-field surface time histories of representative earthquake events and scale them to various PGA levels.
3. Perform the nonlinear dynamic analyses for the seismic responses of the sheet pile wharf under different levels of excitation.
4. Deduce the distribution of the residual displacement at the top of the sheet pile wall with respect to PGA.
5. Estimate the conditional probability that the structural damage meets or exceeds the specified damage state at a given PGA level According to the threshold value of each damage state (see Table 1(a)) and the displacement distribution deduced. Then the fragility curve of each damage state can be established.

More details will be provided in the following sections.

Ground Motion Samples

The Hualien Harbor is located in the eastern coast of Taiwan, which is near the collision zone of the Eurasian continental plate and the Philippine oceanic plate and is thus seismically active. The earthquakes that might have significant influence on the Hualien Harbor are usually near-field ones with relative short durations. However, for the major inland earthquakes due to the dislocation of the faults in Taiwan such as the 1999 Chi-Chi earthquake, although the distance from the epicenter to the Hualien Harbor is relative far, the duration is usually longer than the near-field earthquakes and they are destructive when the magnitude is large enough.

Based the earthquake events from 1991 to 2004 with a PGA at the Hualien Weather Station (HWA019) larger than 25 gal (or, the intensity beyond level III by the definitions of the Central Weather Bureau in Taiwan), it is found that 58% of these events have an epicentral distance less than 20 km. Therefore, the ground motion samples in this study should be around 60 % from near-field earthquakes (here defined as the epicentral distance less than 20 km) to meet the real situation.

The ground motion samples for the fragility analysis of sheet pile wharves of the Hualien Harbor are selected from the records of the seismic station HWA062, which is right in the Hualen Harbor, and HWA019, which is near the harbor. 12 earthquake events of a PGA over 25 gal are adopted, as listed in Table 5, including the mainshock of the 1999 Chi-Chi earthquake and the 2002 Hualien offshore earthquake. 4 of them are far-field earthquakes and 8 of them are near-field ones. The EW and NS direction time histories of each event are respectively scaled to 12 PGA levels, such as 0.1g, 0.2g, 0.3g, 0.379g, 0.4g, 0.5g, 0.557g, 0.6g, 0.7g, 0.8g, 0.9g and 1.0g, making a total of 288 acceleration time histories to serve as the input motions for the dynamic analyses.

Table 5. Ground motion samples for the fragility analysis

No.	Recording Time (UT)	PGA (gal)			Epicentral distance to Hualien Harbor (km)	Duration (sec)
		V	NS	EW		
1	03/31/2002 06:52:51	18.66	42.52	52.28	62.31	90
2	09/20/1999 17:47:15	46.9	132.6	126.44	81.55	90
3	09/10/2000 08:54:44	78	131.59	157.43	12.19	53
4	06/10/2003 08:40:23	13.88	72.02	64.42	53.28	81
5	05/28/1996 21:53:08	39.42	240.4	203.72	8.77	54
6	11/01/1999 17:52:53	31.34	131.6	118.08	69.24	85
7	11/26/1995 19:25:43	24.58	95.1	67.24	2.25	46
8	06/30/2001 04:07:23	52.52	52.1	23.14	10.62	49
9	08/10/2002 09:03:04	10.88	32.48	40.74	16.32	44
10	01/13/2004 09:28:50	3.12	17.64	42.52	16.19	41
11	03/07/2004 13:13:49	5.56	35.64	39.84	2.07	39
12	04/24/2004 15:20:15	28.36	47.02	35.7	14.89	49

Results of Fragility Analysis

The nonlinear dynamic analysis for the seismic response under the excitation of the 288 acceleration time histories were performed using the generated FE models of the sheet pile wharves of the Hualien Harbor. The damage criteria defined in the term of the maximum residual displacement at the top of the sheet pile wall (see Table 1(a)) was adopted since it is easier to quantify the extent of damage.

It is assumed that the maximum residual displacement at the top of the sheet pile wall is lognormal distributed at a specific PGA. Then if the lognormal distribution parameters, the log median and the log standard deviation, are estimated by regression, the conditional exceedance probabilities of each specified damage state at various levels of PGA, or, the fragility curve, can be evaluated according to the displacement threshold value of each damage state in Table 1(a). Results for Wharf No. 8 and Wharf No. 9 are shown as the hollow points in Fig. 11 and Fig. 12, respectively, in which the "moderate" curve means the boundary of the damage levels degree I and degree II, the "extensive" curve means the boundary of degree II and degree III, and the "complete" curve means the boundary of the damage levels degree III and degree IV. Since the "slight" curve, which means the boundary of degree 0 and degree I, is difficult to establish in this case because the displacement threshold value between degree 0 and degree I is not definite, it is not included here.

From the results of the fragility analysis of Wharf No. 8 of the Hualien Harbor, it is shown that when PGA<0.1g, the damage state is hardly higher than degree I; when PGA=0.5g, the probability that the damage meets and exceeds degree II is about 20%; when PGA=0.8g, the probability that the damage meets and exceeds degree III is about 10%; when PGA is up to 1.0g, the probability that the damage reaches degree IV is merely 7%. As for Wharf No. 9 of the Hualien Harbor, the damage state is also hardly higher than degree I when PGA<0.1g; when PGA=0.5g, the probability that the damage meets and exceeds degree II is about 15%; when PGA=0.8g, the probability that the damage meets and exceeds degree III is about 8%; when PGA is up to 1.0g, the probability that the damage reaches degree IV is merely 5.5%.

Parameterization of Fragility Curves

For the need of rapid calculation in earthquake loss estimation, the fragility curves are usually standardized into functions with simple forms and parameters in practice. In TELES, it is assumed that the fragility curve has the form of the lognormal cumulative probability function:

$$F(x) = P(X \le x) = \int_0^x \frac{1}{x\sigma \cdot \sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma} \right)^2 \right] dx \qquad (2)$$

where X is the random variable; μ is the median of ln(X); σ is the standard deviation of ln(X). The log median μ and the log standard deviation σ can be estimated by regression. Then the fragility curve can be expressed only by these two parameters.

Based on this assumption, the fragility curves deduced in the previous section are parameterized, as listed in Table 6. Inserting these parameters into Eq. (2), the standardized fragility curves can be obtained, as the dashed lines in Fig. 11 and Fig. 12. It is shown that the standardized curves are quite close to the original ones. Hence, the lognormal cumulative probability function is appropriate for the simplified expression of the fragility curves of sheet pile wharves.

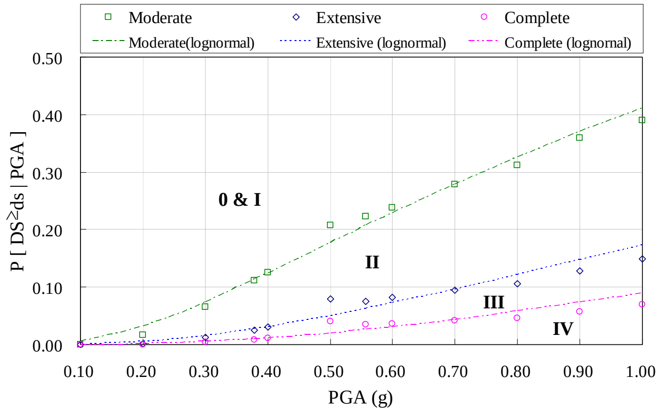


Fig. 11. Fragility curves of Wharf No. 8 of Hualien Harbor

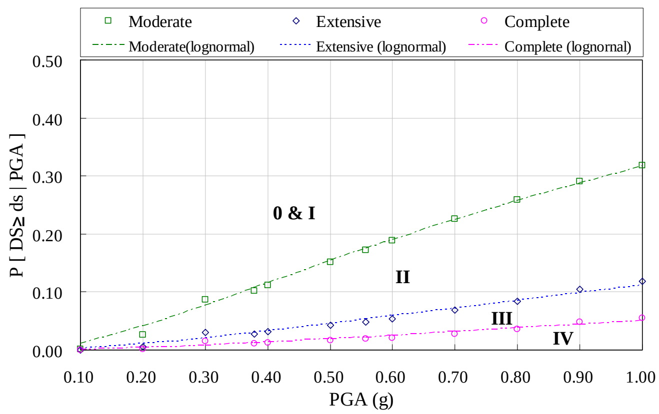


Fig. 12. Fragility curves of Wharf No. 9 of Hualien Harbor

Table 6. Parameters of fragility curves of sheet pile wharves

Corresponding Damage State	Wharf No. 8		Wharf No. 9	
	μ (g)	σ	μ (g)	σ
Moderate	0.22	0.99	0.61	1.28
Extensive	0.93	0.99	1.80	1.48
Complete	1.32	0.98	2.55	1.56

CONCLUSIONS

1. In this study, the FE models of the sheet pile wharves were generate by using the software PLAXIS to perform the nonlinear dynamic analysis for the seismic response.

2. Under the excitation of L1 motions (PGA=0.379g) and L2 motions (PGA=0.557g), the damage levels of Wharf No. 8 and Wharf No. 9 of the Hualien Harbor are in degree II and between degree II and degree II, respectively. Thus, the validity of the model was verified.

3. The procedures of the seismic fragility analysis for the sheet pile wharves proposed in this study give a reasonable estimation of the fragility curves if sufficient and representative ground motion samples are used.

4. The assumption adopted for the parameterization of the fragility curve in this study was proven to be valid, and the fragility parameters that can be used for the earthquake loss estimation were derived

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