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Developing Fragility Curves Based on Endurance Time Method in Comparison with IDA Method, Case Study: East Pile-Deck Wharf of Imam Khomeini Port

Ehsan Shad, Rouhollah Amirabadi Mahdi Sharifi and Ahmad Ghasemi
Department of Civil Engineering, University of Qom, Qom, Iran

Abstract: One of the latest issues in field of marine structures of the country (Iran) is to provide a simple and economic method to repair, improve and retrofit such structures to enhance their seismic resistance. Developing fragility curves has been conducted using non-linear analysis methods, particularly Incremental Dynamic Analysis (IDA) method, so far. Within the recent years, an alternate method called "Endurance Time" (ET) has been proposed to substitute the IDA method. In this study, East Pile-Deck Wharf of Imam Khomeini Port which has a long period has been modeled in three different states including construction (primary) state, damaged state and repaired or improved state and then each state was analyzed using the two methods of IDA and ET. Then, based on results obtained from these two analyses, fragility curves were depicted based on the fully-probabilistic framework provided by pacific earthquake engineering research center to estimate probability of damage occurrence. Findings indicated that regarding considerable time required for implementation of IDA analysis, ET method can be considered as an appropriate and quick alternate method for developing fragility curves.

Key words: Fragility curves, endurance time method, IDA method, Pile-Deck Wharf, Imam Khomeini Port, fully-probabilistic

INTRODUCTION

One of the latest issues in field of marine structures of the country is to provide a simple and economic method to repair, improve and retrofit such structures to enhance their seismic resistance. Development of fragility curves has been conducted using non-linear analysis methods, particularly Incremental Dynamic Analysis (IDA) method, so far. The main objective of this study is to provide fragility curves of the structure based on ET method in comparison with fragility curves resulted from IDA method. The ET analysis method is a kind of time-domain analysis in which performance of structures is evaluated by gradually intensifying ground motions. This research has attempted to evaluate seismic behavior of Pile-Deck Wharfs using ET analysis method and finally, the fragility curves have been developed using the ET method. Seismic fragility analysis is an instrument to determine structural damage probability due to different levels of an earthquake. This instrument is highly important in estimating probable damages due to earthquakes. Input data of this analysis is the ground motion intensity and the output is an estimation of damage expected in the structure. Modeling has been implemented for three different performance states of the Pile-Deck Wharf structure including the structure in its construction (primary) state, damaged state and repaired and improved state, so that, it would be applicable to compare behavior of the structure in the three performance states. Dimensions of the Wharf in the plan are 23×18 m and its natural period is about 3 sec. Soil-structure interaction has been modeled using non-linear Winkler springs (P-Y) and then they have been analyzed using both IDA and ET methods. For this purpose after collecting the required data, East Pile-Deck Wharf of Imam Khomeini Port for each of the three states was modeled in 3D form. Details of such studies have been provided in the following parts.

Literature review: For the first time, Estekanchi *et al.* (2004) proposed the idea of using ET method using exercise test. First, ET method was used for linear evaluation of steel frames (Estekanchi *et al.*, 2004)). In the following by improvements made in accuracy of ET records, a more comprehensive study was conducted in linear state for the same structure (Estekanchi *et al.*, 2007). This method is in fact a simple dynamic pushover analysis which attempts to investigate seismic resistance of structures by analyzing them under effect of a predefined incremental dynamic excitation based on a spectrum. The time that the structure experiences since beginning of the analysis until failure moment is called ET

Corresponding Author: Ehsan Shad, Department of Civil Engineering, University of Qom, Qom, Iran

(Estekanchi *et al*., 2004). Estekanchi and Alembagheri (2012) investigated capability of this method in estimating damage criteria. Riahi *et al*. (2009) considered this method in seismic evaluation of non-linear steel structures. Valamanesh and Estekanchi (2010) investigated seismic response of steel structures under the three-directional excitation analyzed by ET method. Estekanchi and Alembagheri (2012) studied application of ET method to evaluate steel storage tanks located on ground surface. They also compared their results with those obtained by using the method provided in the related code (Estekanchi and Alembagheri, 2012). Hariri and Saouma (2015) used this method for seismic evaluation of steel structures concrete dams and tall concrete buildings (Hariri *et al*., 2014a, b). These studies indicated that ET method has a considerable advantage in reducing and saving calculation costs. Also, its results shall be used after conducting adequate investigation on customary structures, especially, when response of the structure is under the effect of intense non-linearizing factors. It is also important to consider that ET analyses are alike time-domain analyses but ET method uses acceleration functions rather than earthquake records.

First, 3D modeling of the interested Wharf was conducted using SAP2000 Software and then the pushover analysis was implemented to determine capacity of the Wharf and quantify the damage criteria. Afterwards, IDA analysis was conducted to determine the seismic demand. Bayati (2010) evaluated manner of selecting and scaling accelerometers for seismic design of armed-concrete structures against collapse with approach of non-linear dynamic analysis and fragility curves as appropriate instruments to numerically estimate different performance levels. Baneshat (2011) investigated accuracy of shear frame models in estimating seismic responses, using IDA analysis and also conducted a probabilistic investigation to determine safety level of using shear frames corresponding to the main frames. Razavi (2005) in order to improve seismic behavior of a Pile-Deck Wharf, considered an inclined pile by applying a simple fuse and the result indicated that the EBF system applied has appropriately been able to execute the proposed solution while preserving sufficient lateral stiffness within the range about the same value when there is no fuse and at the same time enjoy a ductile structural element.

Fragility curves are considered as the most effective instrument in evaluating damage probability in determined risk levels. Fragility curves are developed based on engineering judgment (ATC, 1985), damage data in relation with past earthquakes (Tahmassebpour and Otaghvari, 2016; Shinozuka *et al*., 2000a) or numerical simulations based on a pseudo-static or dynamic analysis (Padgett and DesRoches, 2008; Shinozuka *et al*., 2000b). Within the recent years, fragility curves have been developed for different kinds of structural systems including armed-concrete frame/wall system, armed-concrete structural walls, steel frames and armed-concrete bridges (Lignos *et al*., 2010; Hwang and Jaw, 1990; Atafar *et al*., 2013; Park and Ang, 1985). Caisson structures and Pile-Deck Wharf structures with vertical steel piles are examples of berthing structures for which fragility curves have been developed (Singhal and Kiremidjian, 1996; Karim and Yamazaki, 2003).

MATERIALS AND METHODS

Introducing of case study: Imam Khomeini Port was built in 1928 in Northwest of the Persian Gulf and at the end of Mousa estuary waterway (with geographical location of 30° and 25 min toward North and 49° and 5 min toward East). This port with area measuring 5500 ha has cargo reception capacity equal to 54.5 mill tons/ear. The Wharf which has been studied in this research is the East Pile-Deck Wharf of Imam Khomeini Port which is now known as the 150000 ton grain Wharf. This Wharf was built around 1951 and has been operated for many years, since, then. This Wharf due to special environmental conditions of the Persian Gulf has been corroded and also has been partially repaired and renovated in several stages. The latest improvement on these Wharfs was concentrated on enhancing loading capacity of the piles using concrete jacket, details of which are provided in the following.

The primary structural system of this Wharf includes filled tubular piles with 15 cm diameter located next to each other with regular space of 4.57 m and the top structure system includes steel transverse and longitudinal beams and a wooden deck as a slab. The piles are connected to each other using vertical longitudinal and transverse bracings. Transverse beams are also located on the piles and their connection with piles is in form of hinge connection. The main and bottom timbers of the wooden deck of this Wharf are located in longitudinal and transverse directions with respect to the Wharf on these beams. Plan and cross-sectional view of the Wharf in construction state together with details of sections are indicated in Fig. 1. This Wharf which was built in 1951 and has been operated afterwards has undergone following damages, since, transverse and longitudinal beams have not been located in the tidal zone, they have had a relative appropriate condition. Connections of piles and transverse beams, except in some cases due to inappropriate collision of vessels have remained mostly sound and intact. Transverse and longitudinal vertical bracings, horizontal bracings in the

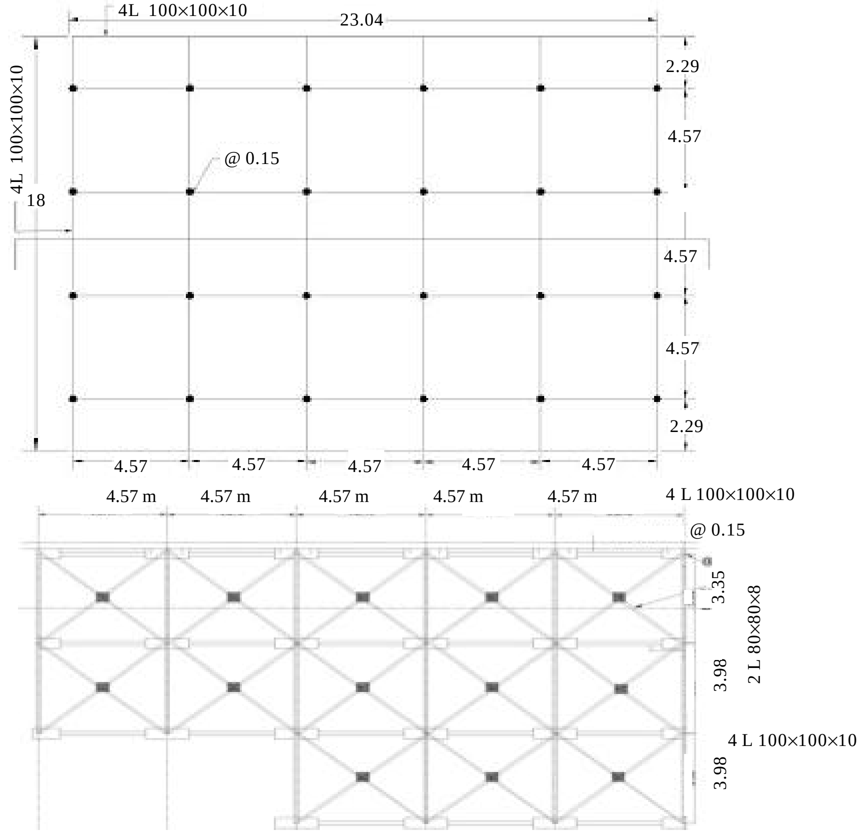

Fig. 1: Plan, cross-sectional view and details of section of the East Pile-Deck Wharf of Imam Khomeini Port in construction state

bottom level of the deck, horizontal reinforcing bars which were in the tidal zone had undergone intense corrosion and needed fundamental repairs. Fenders located in North and South sides of the Wharf also had main defects in a manner that in fact there was no fender for berthing. Also, since, no repair whether general or local had been carried out on these Pile-Deck Wharf structures as of their construction time until the time before the repair and renovation operation and since, these components had been located in the tidal zone, the piles had undergone intense corrosion, so that, their diameter had reduced from 15-13 cm. Some of the piles had undergone buckling and some other had undergone general failure due to impact of vessels (Tahooni *et al.*, 2006).

This repair and improvement has included two main parts such as locally repair of members and repair of vertically load-bearing systems (including deck, transverse and longitudinal beams, piles, etc.) at the same time, to renovate this structure. The general method considered for local and general repair of the load-bearing systems have included removal of the existing wooden deck, cutting and removing of all transverse and longitudinal vertical bracings, reinforcing transverse or longitudinal horizontal rebars, repairing filled steel piles, adding concrete jacket for improving piles below the deck for repairing and adding hollow steel piles with 46 inch diameter and with 18.28 m regular spaces, to establish laterally load-bearing systems for seismic improvement. Figure 2 and 3 indicate the seismic improvement process of East Wharf of Imam Khomeini Port. Also the plan, cross-sectional view and section details of the modeled Wharf at the time of repair and improvement are provided in Fig. 4.

Modeling: Modeling procedure has been implemented using SAP2000, Version 18.1.1. In this research, the comparison has been conducted between three performance states including construction (primary) state, damaged state and repair and improved state. For this purpose, a part of the aforesaid Wharf with 23 m length and 18 m width has been selected to represent general behavior of the structure.

Primary state of the primary Wharf includes 24 filled piles with 15 cm diameter which have been

Fig. 2: The process of constructing 46 inch reinforcing pile to improve seismic behavior of East Wharf of Imam Khomeini Port

Fig. 3: The process of constructing concrete jacket to improve seismic behavior of East Wharf of Imam Khomeini Port

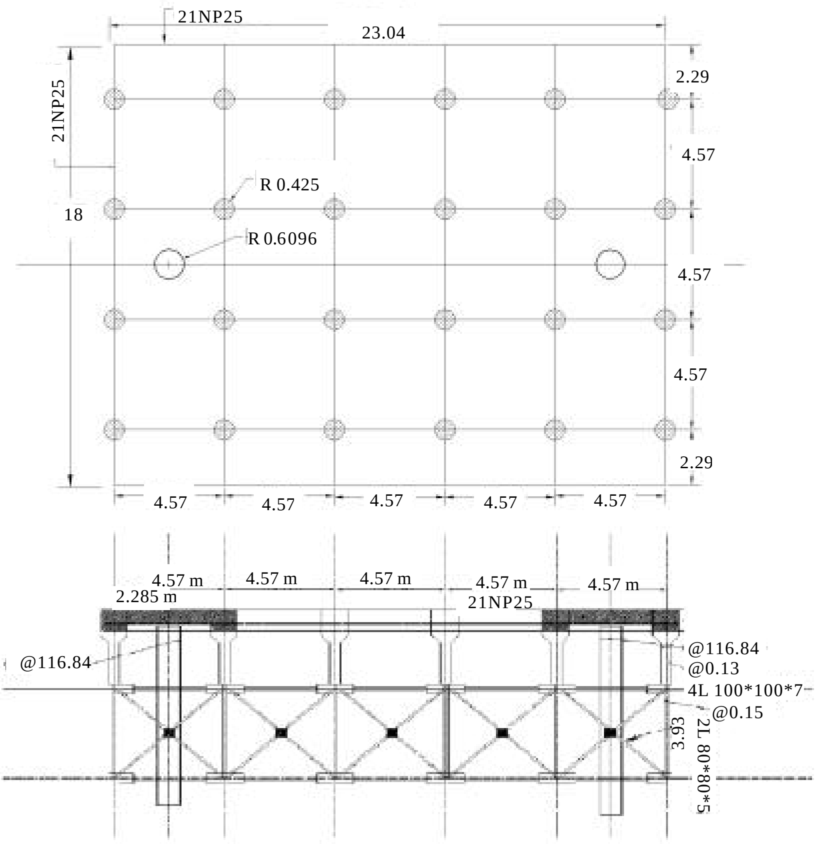

Fig. 4: Place, cross-sectional view and section details of East Wharf of Imam Khomeini Port in repair and improvement state

penetrated into the ground for 30 m depth. Transverse beams have also been located on the piles and had a hinge connection with the piles. In this model, the deck is made of wood and soil layers have been consisted of two layers of silt-clay and one layer of sand. Soil specifications have been provided in Fig. 1. In Fig. 5, primary state of the Wharf is indicated in a 3D Model (Table 1).

Table 1: Soil layer specifications in area of Imam Khomeini Port

E	v	i	c	γ_d	ω	k	h
40-55	0.45-0.50	0	0.15-0.20	1.4-1.5	25-35	CL/ML	6
350-450	0.45-0.50	0	1.5 - 2	155-1.75	20-35	CL/ML	10
400-600	0.30-0.33	33-35	0	1.75-1.95	20-30	SC/SM	14

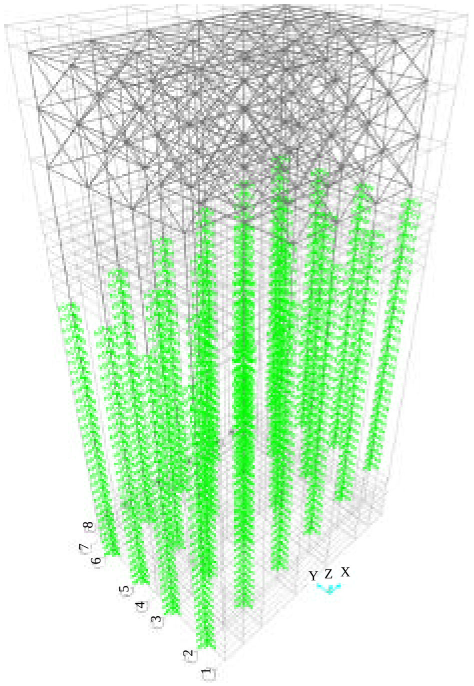

Fig. 5: 3D Model of East Pile-Deck Wharf of the Imam Khomeini Port in construction state

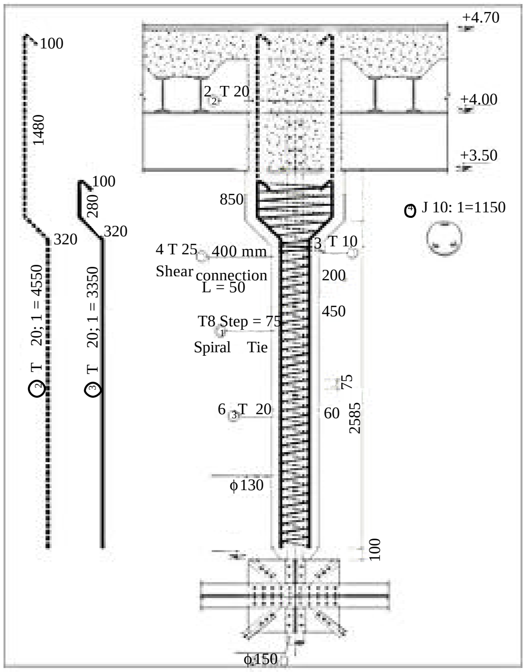

Fig. 6: Specifications of concrete jacket section

In the damaged state, since, neither general nor local repairs have been made on piles of the Wharf, since, its construction time and considering location of these components in the tidal zone, the piles have undergone intense corrosion. In these models, 3 mm corrosion has been considered for piles in the tidal zone. In this state, connection between piles and transverse beams are mostly sound and intact. Transvers and longitudinal vertical bracings, horizontal bracings in the bottom level of the deck, horizontal rebars, those which were in the tidal zone, have undergone intense corrosions and needed fundamental repairs and were not included in the analytic model.

In the improved state of the Wharf, two reinforcing hollow steel piles with 46 inch diameter and also concrete jacket have been added to the model. Details of the section are indicated in Fig. 6. Diameter of piles covered by concrete jacket has been reduced to 13 cm due to sandblast, also the wooden deck has been removed and a concrete deck has been replaced. Transverse and longitudinal beams have been replaced and transverse and longitudinal rebars below the deck have also been reinforced. Furthermore, the bracings below the deck have been removed.

Soil-structure interaction: Pile-Deck Wharfs are structures for which soil-structure interaction shall be appropriately considered in the modeling to be able to extract the proper seismic behavior of the structure. Soil behavior relies on various factors, for this reason, it is very complicated and difficult to provide a model which can include effect of all factors. Hence, for solving problems related to the soil-structure interaction, using simplified patterns is very common. A number of such simplified patters rely on linear elastic behavior theory. One of the aforesaid simplified patterns was proposed by Winkler in 1867 in which deflection of each point in the soil bed is assumed as proportional to extent of stress existing in that point and effect of stresses and displacements of other points are ignored. One of the obvious specifications of this model is its non-continuous behavior. Subgrade reaction method of Winkler has earned special acceptability among engineering society due to its simplicity and real

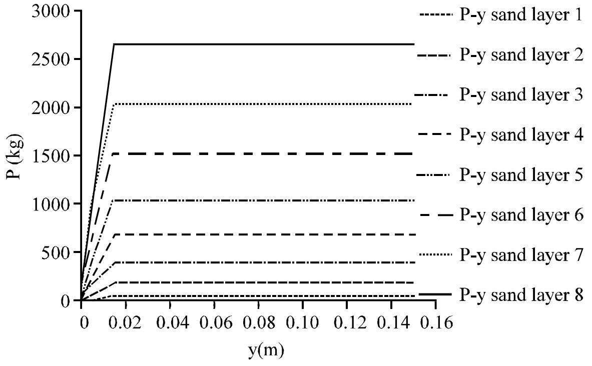

Fig. 7: P-Y Curve for different sand soil layers

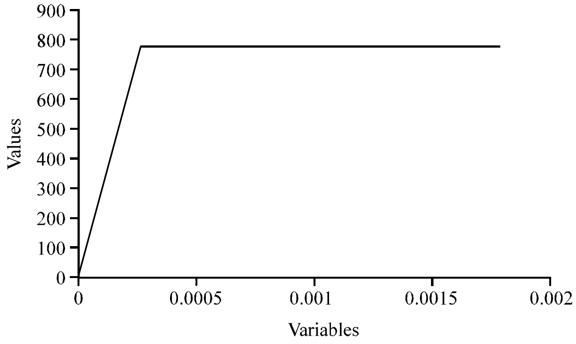

Fig. 8: T-Z curve for sand layers

responses. In this method, the pile has been modeled using moment beam elements surrounded by soil modeling linear and non-linear springs. In this research, lateral reaction of soil exerting on side walls of the piles and the reaction exerted to end of the pile have been calculated based on the related standard (API-RP2A) and have been applied on the model using P-Y and T-Z curves by springs with non-linear behavior. For this purpose, non-linear link elements existing in the software have been used. Typical P-Y, T-Z curves are semi-empirical curves. These curves express the relationship between lateral forces exerted from the pile to the soil element by lateral displacement of this element (Tahmassebpour, 2016; Murchison and O'Neill, 1984). Figure 7 and 8 indicate P-Y and TZ diagram used for the sand soil in different depths.

Behavioral specifications of hinges: In this research, non-linear specifications of the sections have been extracted using moment-curvature diagram to be able to define non-linear behavior of the material and plastic hinges. Moment-curvature diagram has been obtained for the filled-pile and the reinforcing pile using SAP2000 software. Figure 9 and 10 indicate moment-curvature diagram for filled and reinforcing piles used, respectively.

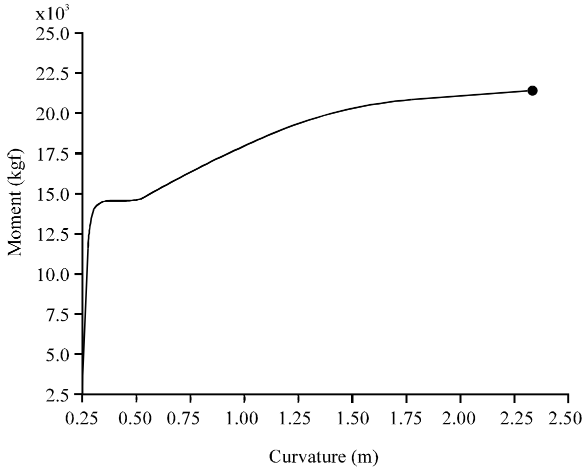

Fig. 9: Moment-curvature diagram for filled steel piles

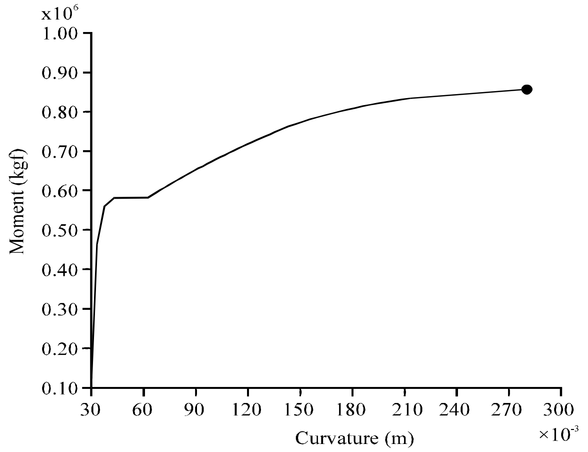

Fig. 10: Moment-curvature diagram for 46 inch reinforcing piles

Endurance time method: ET method has been proposed as a dynamic analysis process based on time domain and in the framework of earthquake engineering. In this method, structures are excited by an acceleration function which is increased gradually. Performance of the structure is investigated based on length of time intervals which can meet interested performance objectives. In ET method in order to prevent from confusion in diagnosing ground motions in simulated accelerometers which are usually compatible with ground motions, increasing acceleration functions are used instead of the accelerometer. The idea of ET method is similar to an exercise tests used by heart physicians when they evaluate their patients and determine heart condition of their patients. In this test, the patient is asked to walk on a treadmill-like device and then speed and slope of the device are increased and this will be continued until the patient becomes exhausted. Afterwards, heart condition of the patient is interpreted based on situation of the patient in each slope and speed he/she has endured. When it is difficult to estimate efficiency parameters of the structure or when relative efficiency between two or more different designs of a structure are being compared, this relatively simple method is able to conduct this comparison with an appropriate accuracy and can indicate performance of the structure. Concept of this method can be described using an imaginary test. Imagine that, we seek to investigate seismic performance of three models of a building which their seismic resistance details are unknown. Imagine that these three models are located on a shaking table and are fixed. The tests starts by a random shaking of the table exerted to the buildings and this shaking becomes very intense. At the beginning, shaking intensity is low and hence, all the three buildings shake but maintain their stability. As the shaking extent increases (T = 10 sec), one of the buildings fails. Imagine this failure has occurred for model A. By elapse of time and increase of shaking intensity (T = 20 sec), the second building also fails which here it is imagined to be the model C. Finally, model B is the last building which fails in this test. According to this test it can be concluded that building A which has failed earlier than the others has the worst performance (Estekanchi *et al*., 2007).

IDA method: Generally, incremental dynamic analysis includes a series of non-linear dynamic analyses under scaled loadings which use a reference loading in which the IMs (Intensity Measures) are selected in a manner to cover all range of behavior of the structure starting from elastic state, then non-elastic state and finally, collapse state and the purpose of taking such action is to achieve DMs (Damage Measures) of structural models in different IM levels which is usually depicted in form of a continuous diagram. In this research, recorded accelerations of the earthquake are exerted to the Pile-Deck Wharf structure and in each step by scaling these accelerations and exerting them to the pile-deck Wharf and implementing non-linear dynamic analysis, behavior of the Wharf structure is recorded and this process continues until in one of the stages, the damage measures exceed the allowed limit or the Wharf collapses.

Selecting excitation functions and scaling: The main difference between ET records is in their target pattern spectrum. The other difference is in the domain of periods covered when producing them which becomes important in non-linear application. Other differences are in the length of records, time steps and manner of primary scaling. Production of ET functions advances gradually and they have been divided into different generations with respect to evolution stages. In the first generation of ET records, compatibility with the spectrum was lost at the increasing time. These records have been only used in the primary papers of this literature which used to explain concept of ET method. In the second generation of records, spectral increase was conducted proportional to the pattern spectrum by using numerical optimization in the range of linear spectrum which were also used in long period by correcting the spectrum in non-linear analysis. The third generation of ET records have also become optimized in non-linear range. In the fourth generation, compatibility is made in record production process with respect to endurance time of intense motion and motion cycles. In this research, ETAh records have been used. These records are the average 7 records selected from FEMA440 and are appropriate for non-linear analyses. The other advantage of these records is higher intensities of excitation up to four times more that the pattern spectrum. In ET method, comparison is made between the results obtained based on values from analysis of the earthquakes and the ET results in the zero time window until the target time. Target time corresponding to each risk level is the time when intensity of the excitation made by ET excitation function is equal to average intensity of reference earthquakes. In this research, the target time is equal to 10 sec. Scaling is conducted for response spectrum of the first 10 sec of accelerometers. Scaling is conducted in compliance with the site spectrum of soil type 2 mentioned in 2800 standard and in period range of 0.9-1.3 T. Table 2 indicates natural period of the primary structure, damaged structure and improved structure.

In Table 3, 12 far-field real earthquake records have been selected for IDA method. Scaling has also been conducted in period range of (0.9-1.3 T) for real records of the earthquake. Figure 11 and 12 indicate the scaled response spectrum for earthquake real record and for ET accelerometer, respectively for Wharf with improved stated as an example. Real earthquake records and ET accelerometers are exerted to the model, toward strong direction of the structures.

Fragility curves: Seismic fragility analysis is an instrument to determine damage probability of structures due to different levels of an earthquake. This instrument is considered as an important step toward estimating damages due to earthquakes. Input data of the analysis is ground motion intensity and its output is an estimation of

Table 2: Natural period of the primary structure, damaged structure and improved structure

Improved structure	Damaged structure	Primary structure
3.25	3.5	3.47

Table 3: Specifications of 12 earthquake selected records

Earthquake names	Magnitude	Station names	Station No.	Component (°)	PGA (g)	R (km)
Landers	7.5	Yermo, fire station	12149	0	0.0152	24.13
Loma Prieta	7.1	Anderson Dam, downstream	1652	270	0.0244	24.32
Northridge	6.8	Castaic, Old Ridge Route	24278	360	0.0514	29.78
Loma Prieta	7.1	Frémont, Mission San Jose	57064	0	0.0127	39.08
Loma Prieta	7.1	Monterey, city hall	47377	0	0.0730	54.86
Northridge	6.8	Lake Hughes 1, Fire Station 78	24271	0	0.0860	43.60
Morgan Hill	6.1	Gilroy, Gavilon College Phys Sci Bldg	47006	67	0.1150	15.70
Westmorland	5.9	Superstition Mth Camera	-	45	0.0810	19.26
Palmsprings	6.0	Fun valley	5069	45	0.0710	16.80
Morgan Hill	6.1	San justo Dam (RAbut)	-	360	0.1090	31.88
San Fernando	6.5	Pasadena, CIT Athenneaum	80053	90	0.1040	40.00
San Fernando	6.5	Pearblossom pump	269	21	0.0590	46.00

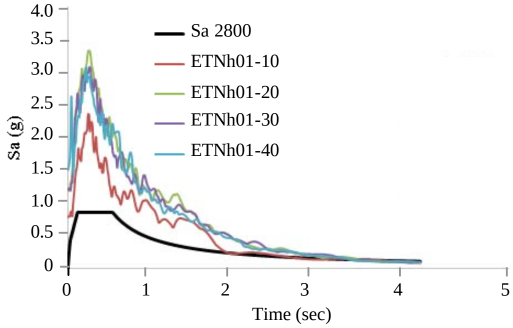

Fig. 11: Scaled response spectrum of ET accelerometer

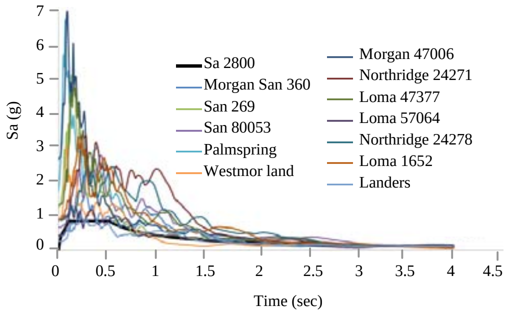

Fig. 12: Scaled response spectrum of real earthquake records

expected damage in a structure. Interpretation of ground motion intensity and also interpretation of the damage occurred in fragility analysis are considered as key issues. Ground motion intensity is either expressed as a quantity by parameters determining ground motion or as a quality by using fixed scales. Also structural damage is either expressed in a quantitative manner by several damage criteria or in a qualitative manner such as descriptive damage states. Fragility data are expressed as a relationship between ground motion and probability of reaching different damage states or beyond them. Since, the fragility data do not indicate seismic risk in location of the structure, it is not sufficient by itself to provide estimations for expected damages due to earthquakes. Fragility data can provide estimations of seismic risks only when merged with earthquake risk and damage data. Fragility data shall be obtained in a probabilistic framework due to uncertainty existing in ground motion, soil characteristic and structural parameters of the system. However, it has been proved that uncertainly in ground motion and soil characteristics is much more than uncertainty in structural parameters. Therefore, many researchers assume structural parameters as fixed and constant but some other researchers in addition to ground motion and soil characteristics have also considered variations in structural parameters.

RESULTS AND DISCUSSION

Fragility curve has been provided in this part for three performance states of the structure, after providing diagram of displacement in the Wharf Deck by ET method and IDA method. The results include displacement diagram and absolute value of maximum displacement in the Wharf Deck in which the horizontal axis represents time and the vertical axis represents displacement. Finally, fragility curves of the both analysis methods have been compared with each other.

ET method result: In this part, results obtained from ET analysis have been provided in three states of the Wharf as mentioned above. Response of the structure for ET functions increases as the trend increases and ET curves are mostly depicted as increasing curves. Response of the structure is extracted for the interested parameter and absolute value of responses are obtained. Then in each time, the maximum response until that time is considered. Hence, ET response curves are in a stair form. To remove and avoid accidental effects, usually average response of three ET analyses is obtained and used. For all of the results, absolute value of maximum responses and average absolute value of maximum responses are also indicated.

IDA method result: In this part, results of IDA analysis in three states of the Wharf have been provided. In order to compare behavior of the three states such as primary, damaged and improved models against 12 real earthquake records, average absolute value of deck displacement has been calculated. As it was predictable, displacement in the damaged Wharf is much more that the primary and improved Wharfs.

Development of fragility curves based on ET and IDA methods: Fragility analysis is simply conducted in four steps. The first step is to define damage limit states. The second step is to create a response matrix for structures under effect of earthquake events with scaled PGA levels. The third step is to execute statistical analysis for extracting fragility curves. The final step is to simplify fragility curves obtained for simple applications. Also, the comparison between fragility curves of the three primary, damaged and improved structures is indicated in the two methods

Comparison between ET and IDA fragility curves: As it can be observed, the fragility curve developed using ET method compared to that of IDA method has more appropriate conformity with operation condition with 18% difference. This result is also valid in repairable state. In near-collapse state, difference between these two methods can be observed up to 23%. This finding indicates that according to considerable time required for implementing incremental dynamic analyses, the endurance time method can be an appropriate and quick substitute for developing fragility curves. Of course, it is required that this method be used in more research and on different kinds of structures with broader range of periods.

CONCLUSION

In this research, fragility curves have been developed and compared using IDA and ET analysis methods. This study has been conducted on Pile-Deck Wharf structure located in Imam Khomeini Port. This Wharf has a long period and is considered as a ductile structure. This Wharf has been modeled in three different states including the construction (primary) state, damaged state and improved state and then each of them has been analyzed by the two methods including time-domain and ET. Then, based on the results obtained from these two analyses, the fragility curves have been depicted based on a fully-probabilistic framework provided by Pacific earthquake engineering research center to estimate the damage probability. Comparison made between fragility curves of the improved model and the primary model indicated that vulnerability of the improved model is less that the primary model and the improved model has less fragility.

RECOMMENDATIONS

Furthermore, according to the considerable time required for implementing incremental dynamic analyses, ET method can be considered as an appropriate and quick substitute for developing fragility curves. Of course, it is required that this method be used in more research and on different kinds of structures with broader range of periods including buildings, etc.

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