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Study on the Influence of Earthquake Duration on the Dynamic Response of Pile-supported Wharf in Deep Water Area

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Abstract. In order to study the influence of earthquake duration on the dynamic response of pile-supported wharf in deep water area, this paper takes a typical steel pipe pile-supported wharf as the research object. This paper establishes the finite element model of pile-supported wharf. And by applying earthquake waves with different duration to the structure, the displacement response of the piled wharf, the energy dissipation ratio of plastic hinge, and the destruction process were analyzed. The study results show that the influence of earthquake duration on the displacement response of the structure is less but the influence on the parameters which are characterizing the earthquake energy dissipated by structure is significant, and the larger the amplitude of the earthquake waves is, the more significant the influence is. The parameters that characterize the earthquake energy dissipated by structure can provide a good indication of the damage level of the pile-supported wharf under earthquake with different durations. As a simple method, it can be preliminarily judged by the moment-curvature relation curve; when studying the influence of earthquake's duration on the structure, an appropriate duration threshold should be chosen based on the type of structure.

1. Introduction

Amplitude, spectrum and duration are three elements of earthquake. At present, many researchers have taken into account the two factors of amplitude and spectrum characteristics in structural seismic design and seismic hazard analysis, but there is not enough attention to the study of duration. However, in many cases, especially under the action of strong earthquakes, the damage degree of the construction depends not only on the amplitude and frequency spectrum of the earthquake, but is also closely related to the duration of the earthquake. A large number of examples at home and abroad, such as the *Wenchuan Earthquake* in 2008[1] and *the Great East Japan Earthquake* in 2011[2], have proved that the long duration earthquake can cause more serious damage to the structure and even collapse, so its influence cannot be ignored [3,4]. Meanwhile, the study shows that cumulative damage can better reflect the influence of seismic duration [5,6].

In the current code for seismic design [7], the effective duration of the earthquake used in the time history analysis is generally (5~10) times the fundamental period of the structure, that is, the displacement of the structure vertex can be reciprocated (5~10) times in the basic cycle [8]. However, the measured data shows that the duration of earthquake has large differences, ranging from a few seconds to several hundred seconds. The longer the duration is, the greater the impact on the structure is. Therefore, according to the dynamic characteristics of the building, it is necessary to analyze the dynamic response and mechanism of plastic damage of structures under different duration earthquakes.

In the seismic study of pile-supported wharfs, many scholars at home and abroad have studied the spectrum and amplitude of earthquakes and have achieved certain results [9,10], but the research on pile-supported wharf under the action of different duration earthquakes is not clear. Moreover, with the development of large-scale, deep-water areas in port terminals, the limitations of previous studies have become more pronounced.

Therefore, this paper takes the pile-supported wharf of a typical steel pipe pile in a deep water area as the research object, establishes a finite element model, and performs nonlinear time-history analysis by applying different duration earthquakes to the structure. Based on the analysis of the displacement of the pile top and the energy dissipation analysis results of the non-linear plastic hinge, the damage and failure process of the pile-supported wharf under different duration earthquakes was analyzed, and the influence mechanism of the duration to the dynamic response of the structure was explored.

2. Research background

A pile-supported wharf with steel pipe piles was selected as the research object. The normal direction of the wharf is 24.0m and there are 5 rows of piles in total. The upper reinforced concrete platform is 11.0m wide and 400mm thick. The wharf structure is supported by 4 steel pipe vertical piles, and the piles are numbered ① to ④ from the sea side to the land side. The steel pipe uses Q235 steel. Among them, pile ① steel pipe outer diameter 600mm, wall thickness 9mm, the remaining pile (②~④) steel pipe outer diameter 700mm, wall thickness 9mm. The standard section of the wharf structure and the foundation of the site are shown in Figure 1. It is a class II site [11].

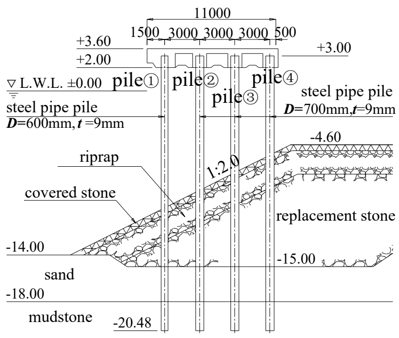

Figure 1. Sectional drawing and soil layer's drawing of wharf structures.

3. Finite element numerical simulation analysis method

3.1. The establishment of finite element model

Figure 2 shows the wharf finite element model. The concrete platform adopts plate unit, and the pile is modeled by the beam element. The interaction between the pile body and the foundation is achieved by setting the equivalent springs [12]. The stress-strain curve of steel pipe pile is shown in Figure 3.

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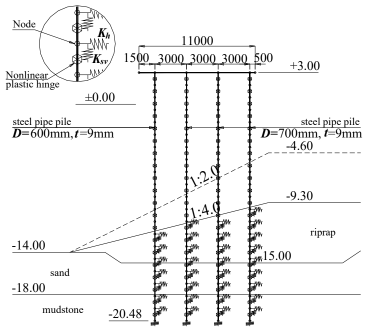


Figure 2. Finite element model of wharves.

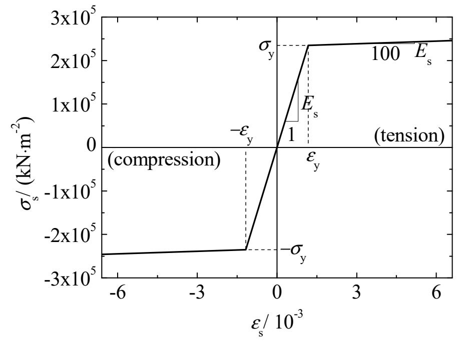
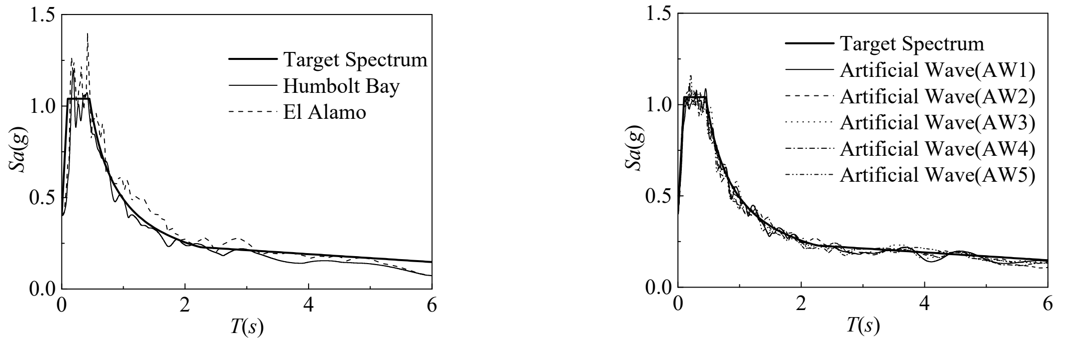


Figure 3. Stress-strain curve of steel pipe.

3.2. Selection of earthquake waves

In order to study the influence of duration on the dynamic response of pile-supported wharfs, two actual seismic waves and five artificial waves were selected based on the target spectrum calculated according to the reference code [11]. The actual seismic waves use the *Humbolt Bay seismic wave* and *El Alamo seismic wave* in the *PEER strong earthquake database* [13]. Based on target response spectrum, *SeismoArtif* is used to get artificial waves of different durations. The response spectrum of selected seismic waves is shown in Figure 4, and its important duration [14] is shown in Table 1. In order to fully develop the plastic hinge and reflect the influence of duration on the dynamic response, the peaking ground acceleration was adjusted to 620Gal and 1000Gal. In the nonlinear time history analysis, the seismic waves are loaded from the bottom of the piles.



(a) Response spectrum of actual waves. **(b)** Response spectrum of artificial waves.

Figure 4. Response spectrum of earthquake waves.

Table 1. The duration of selecting earthquake waves.

Earthquake	Humbolt Bay	El Alamo	AW1	AW2	AW3	AW4	AW5
Duration(s)	20.96	41.91	25.66	40.62	56.83	69.91	87.27

4. Analysis of Influence of seismic duration on dynamic response of pile-supported wharf

4.1. Influence of duration on displacement of pile top

Figure 5 shows the maximum displacement of piles top under artificial seismic waves with different durations. From Figure 5, we can see that the maximum displacement fluctuates with the increase of the seismic duration. Combining the data in Table 2, we can see that without considering the actual seismic wave, the variance of the maximum displacement is extremely small, which means that the change in duration will have an impact on the structure displacement, but the impact will be minimal.

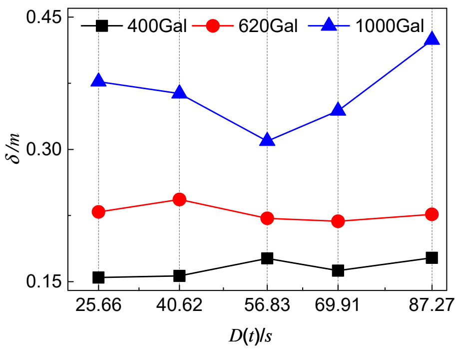


Figure 5. Maximum displacement of pile-tops.

Table 2. Variance of maximum displacement of pile-tops.

Amplitude / Type of waves	400 Gal	620 Gal	1000 Gal
Artificial waves	9.19E-05	7.24E-05	0.00143
Artificial and actual Waves	0.000124	0.000286	0.00207

Compared to the duration, the maximum displacement of the wharf is more affected by the amplitude and spectrum of the ground motion. From Figure 5, it can be seen that under the same duration ground motion, the maximum displacement increases sharply with the increase of the amplitude of the ground motion. Based on the data in Table 2, considering the actual seismic wave, the variance of the maximum displacement significantly increases, which indicates that the maximum fluctuation of the displacement is aggravated. This phenomenon is especially obvious in the small earthquake amplitude. All the artificial seismic waves are fitted by the same target response spectrum, so the spectral characteristics are very close. The actual seismic waves are only screened according to the target response spectrum, so the spectral characteristics are different.

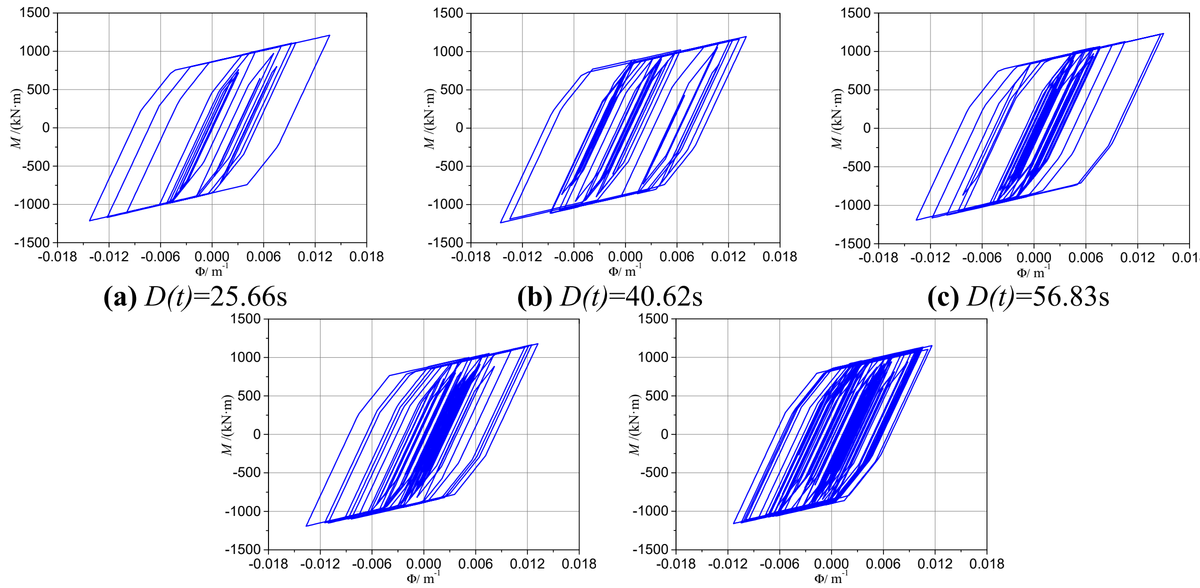
From the above analysis, we can see that the influence of the spectrum, amplitude, and duration of ground motion on the displacement of the pile-supported wharf is coupled. With the change of amplitude, the influence of duration and spectrum on displacement will also be different. When the amplitude is small, the effect of the frequency spectrum is obvious, and the coupling effect of duration is not significant. However, when the amplitude is larger, the longer the duration is, the greater the impact on the pile-supported wharf is.

4.2. Influence of duration on energy dissipation of nonlinear plastic hinge

Table 3 shows the energy dissipation ratio of the plastic hinge of the structure under the artificial seismic waves. Among them, the artificial seismic wave AW1 with 25.66s duration was used as a measure to normalize plastic hinge energy consumption. It can be seen from Table 3 that, with the same amplitude, the energy dissipation of plastic hinge increases significantly with the increase of the duration, indicating that the duration has a significant influence on the parameters which characterize the seismic energy dissipated by the structure. In addition, when the amplitude increases, the incremental ratio of plastic hinge energy consumption gradually decreases. This is because when the amplitude increases, more plastic hinge reaches the yield limit and cannot dissipate to consume seismic energy.

Table 3. Energy dissipation ratio of plastic hinge.

	AW1	AW2	AW3	AW4	AW5
400Gal	1	1.36	1.55	1.76	1.98
620Gal	1	1.20	1.43	1.64	1.87
1000Gal	1	1.01	1.23	1.59	1.78



(a) *D(t)*=25.66s **(b)** *D(t)*=40.62s **(c)** *D(t)*=56.83s

(d) *D(t)*=69.91s **(e)** *D(t)*=87.27s

Figure 6. Moment-curvature (*M*-) relation curve of pile ④-top.

Figure. 6 is the moment curvature relation curve of the top of the pile ④ under the artificial seismic waves with amplitude of 620 Gal and different durations.It can be seen from figure.6, the contour range of the moment-curvature relationship curve does not change with the change of the duration, that is, the extremums of the moment and curvature are not affected by the duration. However, with the increase of the duration, the internal density of the moment curvature curve is gradually increased, which means that the wharf enters a higher degree of nonlinearity, and the structure absorbs and dissipates more seismic energy, and the structure is more easily destroyed. The same rules can be obtained when the amplitude is 400 Gal and 1000 Gal.

4.3. Analysis of damage process of pile-supported wharf

Table 4 is the sequence and time node of pile damage under the artificial seismic waves with amplitude of 1000 Gal and different durations. Among them, the first yield limit is just entering the plastic stage, and the second yield limit is reaching the full plasticity.

Table 4. Timing of damage development of wharf (1000 gal).

The state of piles	AW1	AW2	AW3	AW4	AW5
Pile④: the 1st yield limit	2.48	3.85	2.11	1.32	4.18
Pile③: the 1st yield limit	2.55	3.88	2.54	1.90	4.27
Pile②: the 1st yield limit	6.11	3.95	2.56	1.93	7.46
Pile④: the 2nd yield limit	6.13	4.66	2.57	1.95	7.47
Pile③: the 2nd yield limit	10.06	5.24	2.61	3.77	7.81
Pile①: the 1st yield limit	10.09	5.25	2.66	3.79	7.82
Pile②: the 2nd yield limit	10.10	5.69	3.77	3.86	7.83
Pile①: the 2nd yield limit	10.96	5.74	4.12	4.51	7.89

From Table 4, it can be seen that with the increase of duration, the sequence of the damage state of the pile doesn't change obviously, following the order of ④-③-②-④-③-①-②-①. This is because the depth and stiffness of the pile near the land are larger than that of the pile near the sea, so the plastic development space of the piles near the land is smaller than the pile near the sea, and it is prone to damage. It can be found that with the increase of the duration, the time required for the pile-supported wharf structure to enter plasticity until reaching full plasticity is reduced, and the time interval of each yielding node gradually decreases.

From Table 4, it can be seen that when the duration is different, the time for the wharf structure to enter plasticity is also different. This is because the material determines the damage threshold of the structure. When the input energy is sufficient, the structure will yield. On the other hand, (5% - 95%) important duration is defined by the time period when the accumulated energy released by the ground motion reaches between 5% and 95%. The definition of duration only considered the stronger vibration, but the weak vibration sustained for a long time can also cause structural damage.

5.Conclusions

(1) The influence of the spectrum, amplitude, and duration of ground motion on the displacement of the pile-supported wharf is coupled. With the change of amplitude, the influence of duration and spectrum on displacement will also be different. When the amplitude is small, the effect of the frequency spectrum is obvious, and the coupling effect of duration is not significant. However, when the amplitude is larger, the longer the duration is, the greater the impact on the pile-supported wharf is.

(2) When the amplitude is same, the duration has significant influence on the parameters that represent the energy dissipation of the pile-supported wharf. With the increase of the duration, the internal density of the moment curvature curve is gradually increased, which means that the wharf enters a higher degree of nonlinearity, and the structure absorbs and dissipates more seismic energy, and the structure is more easily destroyed.

(3) The duration has significant influence on the parameters that represent the energy dissipation of the pile-supported wharf. The effect of duration should be considered in areas where long duration earthquakes may occur. The parameters representing the energy dissipation of the structure can provide a good indication for the damage level of structure under different duration ground motions. As a simple method, it can be preliminarily judged by the moment curvature relation curve.

(4) Duration has no obvious effect on the sequence of the damage state of the pile. With the increase of the duration, the time required for the pile-supported wharf structure to enter plasticity until reaching full plasticity is reduced, and the time interval of each yielding node gradually decreases.

Acknowledgments

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