Al-Nahrain Journal for Engineering Sciences **NJES** 27(1)32-37, 2024
http://doi.org/10.29194/NJES.27010032

Performance of Single Degree of Freedom (SDOF) Structures Exposed to the Near-Fault Earthquakes

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Paper History:

Received: 17th Nov. 2023

Revised: 24th Dec. 2023

Accepted: 2nd Jan. 2024

Abstract

The unique features of near-fault earthquakes could cause structural responses very different from those of the other types of ordinary earthquakes. Thus, it is important to highlight the effect of near-fault earthquakes since many buildings and structures located near the faults cannot withstand high levels of shaking because it does not take into consideration this distinctive type of earthquake in the design. This paper aims to calculate structures' seismic response with a system of Single-degree-of-freedom exposed to near-fault earthquakes. Strong ground motion data were taken for different events in different places around the world and the prism software program is utilized for this objective. A parametric study considering shear wave velocity (VS30), the pulse period effect, and fault mechanism including the effect of the Strike-slip fault and Dip-slip fault has been conducted. The findings revealed that peak displacement requirements are observed in a nearby of the pulse period limits. In addition, it is noticed that there is an obvious increase in spectrum demand with longer pulse periods.

Keywords: Near Fault Earthquake, SDOF, Pulse Period, Shear Wave Velocity, Fault Mechanism.

أداء المنشآت ذات نظام (الحركة بدرجة حرية واحدة) المعرضة للهزات الارضية القريبة من الصدع

آية حميد مهاوش ، د.حسام كاظم رسن

الخلاصة:

ان الخصائص المميزة للهزات الارضية القريبة من الصدع يمكن ان تحدث استجابة للمنشأ تختلف عن تلك التي تحدث عند تعرضه للهزات الاعتيادية الاخرى . وبذلك من المهم تسليط الضوء على تأثير الهزات الارضية من هذا النوع حيث ان الكثير من المنشآت و الابنية القريبة من الصدع غير قادرة على مقاومة هذه المستويات العالية من الاهتزازات بسبب عدم التركيز على هذا النوع المميز من الهزات الارضية عند التصميم . يهدف هذا البحث إلى تقييم أداء المنشآت ذات نظام(الحركة بدرجة حرية واحدة) المعرضة للهزات الأرضية القريبة من الصدع. وقد تم أخذ بيانات الهزات الأرضية القوية في أماكن مختلفة حول العالم وتم استخدام برنامج (prism) لتحليل الاستجابة الزلزالية للهياكل ذات نظام الحركة بدرجة حرية واحدة. تمت دراسة المتغيرات مع الاخذ بنظر الاعتبار سرعة القص الموجي, تأثير مدة النبضة, , آلية الصدع بضمنها تأثير نوعي الصدع (Strike-slip) و (Dip-slip). توصلت النتائج إلى ان ان ذروة الإزاحة تحدث حول نطاق مدة النبضة الموجية (Tp) و أن منحنى طيف الاستجابة الزلزالي يزداد بشكل واضح مع الفترات الموجية الاطول.

1. Introduction

Ground motions reflect the characteristics of the source site, travel path, process of rupture, source of seismic, and local site factors. Subsequently, the characteristics of an earthquake around an active fault may vary significantly from those observed in the faraway region. Near -fault ground motion record criteria cause reactions that differ from those which examined at far-field ground motion. Near-fault earthquakes are acknowledged to possess a noticeable forward directivity in addition to fling step. [1]. If the slip's direction at the faults is allied with the site and the rupture front extends toward the site, the effects of forward directivity rupture will happen. Nonetheless, in a specific event, not all near-fault regions will encounter the impacts of forward directivity rupture. The opposite effect of the forward directivity is the backward directivity effect, which occurs if the rupture extends far from a specific site and causes motions with long-duration that show at long periods a low amplitude[2]. On the same station, the normal component of the fault is greater relative to the parallel component of the rupture for the maximum value of ground acceleration. At the forward directivity zone, the record of the velocity is marked by long-duration pulse-type motion. When designing the structures for near-fault events, this pulse-type motion's impact on the responses is vital. The small travel distance of the earthquake waves in the near-fault regions does not provide sufficient time for the high-frequency energy to be damped out of the records, as is commonly found in far-field earthquakes[3].

Fault length could vary from a limited millimeters to a lot of kilometers. Generally, frequent displacements are created by faults during geological time. Throughout an earthquake, the rock on one side of the rupture plane moves unexpectedly relative to the rocks on the opposite side. The fault plane might be, vertical, horizontal, or at any angle. If the faults show a motion along the dip plane that would be called dip-slip faults which are categorized either as normal or reverse based on how they move. However, Strike-slip faults are faults that move horizontally and are referred to be right-lateral or left-lateral. Finally, Oblique-slip faults are described as faults that exhibit both dip-slip and strike-slip motion [4]. Figure 1, shows a diagram that illustrates the different fault types in the tectonic earthquakes and their mechanism [5]. Some studies that take into consideration the impact of near-fault earthquakes are summarized below.

Liu [6], presented a study that included site effect and fault type factors in order to determine the attenuation relations of the PGV furthermore the PGA in Taiwan. Utilizing 92 earthquakes and 2852 accelerograms with Mw magnitudes that vary from 4.0 to 7.7, the regional attenuation relationships were established. Thus, to integrate a site-effect factor and decrease the anticipated ground motion standard deviation for designing purposes, two models are employed: Data from 65 strong-motion stations are utilized in Mode1. However, data from 46 strong-motion sites with specified VS30 are utilized in Model 2. The outcomes indicate that, when compared to reverse or normal fault types, the fault-type amplification factor for strike-slip fault types decreases rapidly with increasing magnitude. When evaluating the overall residuals standard deviations among the actual and expected values prior to and following including the (VS30) and fault-type variables, the variance in the standard deviation for PGA is 2.3%. However, the standard deviation for PGV is notably lowered by roughly 11.6%. Also, it is found that the PGA interevent residual is less correlated with VS30 than that of the PGV because the PGA is a complicated function of VS30.

As a useful choice, the SDOF system is frequently used for evaluating seismic analyses [7–13]. Chopra[14], Compares the response spectra of inelastic and elastic far-field earthquakes to those of near-like pulse earthquakes. This study used a group of 15 ground motions in the near-fault areas which are from the Morgan Hill (1984), Imperial Valley (1979), Kobe (1995), Northridge (1994) Erzincan (1992), and Loma Prieta (1989) ground motions. Besides that, a series of 15 far-field earthquakes were considered, which included earthquakes verified on Jrm soils and rock's locations through nine various earthquakes in the United States. The selected magnitude of the earthquakes ranges about (5.7 to 7.7), considering that the distances of the ground motion stations to the epicenter can vary between (12km to 64km). Since it has been proven that the normal component of the fault for the chosen records is more severe than that of the parallel component of the fault, this investigation focuses on its inelastic and elastic response spectrum. Figure 2 shows the difference between the displacement, velocity, and acceleration time histories of the fault normal component at the near-fault station and the far-field station. For a near-fault record, it is noticed that the velocity-sensitive area gets smaller, while its displacement-sensitive and acceleration-sensitive areas get significantly larger compared to a far-fault record. Yalcin[15], studies the influence of the components of high-frequency near-like pulse earthquakes with the impact of forward directivity rupture on the seismic responses of inelastic and elastic SDOF seismic isolated and regular systems. Findings show that the content of high-frequency near-fault earthquakes has a major impact on short period elastic and inelastic structures that have high yield strength exposed to this type of earthquake. Cheng[16], studies the energy seismic response for the SDOF structures under Long-Period earthquakes. In the research, the energy distribution rule and the elastoplastic seismic energy response of SDOF structures are assessed using a method of energy-based design for two kinds of specific long-period earthquakes. Hysteretic energy, damping energy, and input energy is linked to the ground motion features and the structure's dynamic characteristics, including the earthquake's magnitude, the coefficient of ductility, the condition of the site, the distance of the source-to-site, the damping ratio, the yield stiffness ratio, and so on. Research results show that through the total period, all damping energy spectra, hysteretic energy, and the input energy of structures exposed to far-fault and near pulse-like earthquakes are bigger than those under ordinary earthquakes.

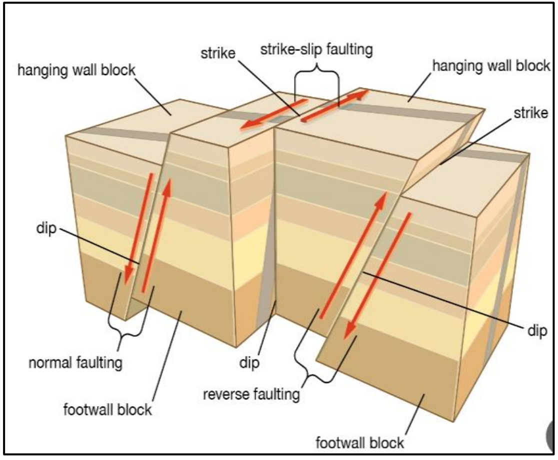

Figure (1): Types of faults in tectonic plates **[5]**.

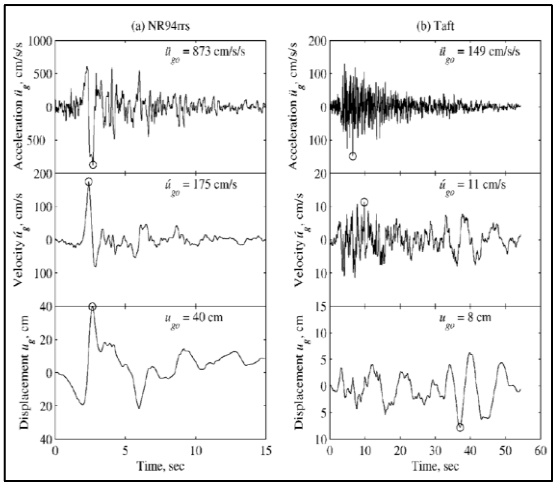

Figure (2): (a) Fault normal component for earthquake of Northridge at the near fault station, (b) Fault normal component of Kern County earthquake at the far-field station [14].

2. The Selected Earthquake Records

The Pacific Earthquake Engineering Research Center (PEER) ground motion database [17] is utilized to elect ground motions for analysis purposes. A group of 17 near–fault earthquakes were chosen as illustrated in Table 1. The near-fault earthquakes magnitudes vary from 5.74 to 7.2 which have a nearest distance to the rupture fault not exceeding 12km. The prism software program is utilized for the analysis seismic response for structures recognized as Single DOF systems. Major characteristics of this software involves an adjustment for ground motions, computation of response time histories of different hysteresis models, and the creation of inelastic and elastic response spectra. The fault-normal component would be used for all analyses. Knowing that all records are scaled to 0.3 PGA for a fair comparison. Finally, it is important to recognize the phenomenon of the strength reduction factor (R), which can be identified as a percentage of the elastic strength to the yield strength as mentioned in the equation below. It is utilized to compute the inelastic SDOF systems strength demand. The rate of (R) depends on the ductility of the structure and Figure 3 shows diagram which illustrates the concept of response reduction factor [18].

$$\boldsymbol{Ry} = \frac{\boldsymbol{fel}}{\boldsymbol{fy}}$$

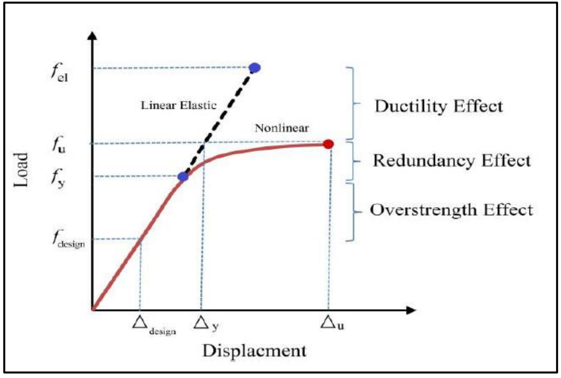

Figure (3): Response reduction factor diagram [18].

3. The Shear Wave Velocity Effect (VS30)

The effects of the local site show a crucial influence on the earthquake characteristics. The velocity of shear-wave to depth 30 m (VS30) is a site condition parameter that has been commonly used to identify the site class in codes of buildings. Table 2, illustrates the VS30 relationship with soil class [19]. However, to study the effect of (VS30), two near-fault records are selected which are the earthquake of Imperial Valley-06, El- Centro - Array #10 sta., and the earthquake of Morgan Hill, Gilroy Array- #6 sta. both are strike-slip fault mechanisms, and their VS30 is equal to 202.85 m/sec and 663.31 m/sec in that order. Figure4 and Figure 5 shows their acceleration time history. The response was evaluated in the elastic state with a damping ratio of 5%. However, Figure 6 revealed the spectrum response of acceleration of the selected two near-fault records.

Table (1): The selected Near-fault earthquakes (NFGM).

Earthquake	Year	Station	Mw[1]	Rrup [2](Km)	Mechanism
Coyote Lake	1979	Gilroy Array #2	5.74	9.02	Strike-slip
Coyote Lake	1979	Gilroy Array #3	5.74	7.42	Strike-slip
Imperial Valley-06	1979	Brawley Airport	6.53	10.42	Strike-slip
Imperial Valley-06	1979	EC County Center FF	6.53	7.31	Strike-slip
Imperial Valley	1979	El Centro Array #10	6.53	8.6	Strike-slip
Irpinia Italy-01	1980	Bagnoli Irpinio	6.9	8.18	Normal
Irpinia Italy-01	1980	Sturno (STN)	6.9	10.84	Normal
Morgan Hill	1984	Gilroy Array #6	6.19	9.87	Strike-slip
Chi-Chi, Tiawan-04	1999	CHY074	6.2	6.2	Strike-slip
Cape Mendocino	1992	Bunker Hill FAA	7.01	12.24	Reverse
Niigata, Japan	2004	NIG021	6.63	11.26	Reverse
Niigata, Japan	2004	NIGH11	6.63	8.93	Reverse
Chuetsuoki,Japan	2007	Joetsu Kakizakiku Kakizaki	6.8	11.94	Reverse
Darfield, New Zealand	2010	HORC	7	7.29	Strike-slip
Darfield, New Zealand	2010	TPLC	7	6.11	Strike-slip
El Mayor- Cucapah, mexico	2010	El Centro Array #12	7.2	11.26	Strike-slip
El Mayor -Cucapah, mexico	2010	Westside Elementary School	7.2	11.44	Strike-slip

M [1] : Moment magnitude of earthquake, Rrup [2] : nearest distance to the fault plane

Table (2): the Vs30 relationship with soil class [19].

Types of Soil	**Soil /Rock Category**	**Typical Shear Wave Velocity (Vs30) m/sec**
A	Hard rock	>1500
B	Rock	760-1500
C	Soft soil /Dense soil	360-760
D	Stiff Soil	180-360
E	Soft Soil	<180
F	Special Soils required different estimation	

It is noticed from Figure 6 that the selected earthquake with a higher value of VS30 provides an acceleration response higher than that of the lower value of VS30, with a ratio increase about 23% at the peak. In another words, the soil type D (Stiff Soil) gives an acceleration response lower than that of the soil type C (Dense soil/soft soil).These findings are consistent with [20].

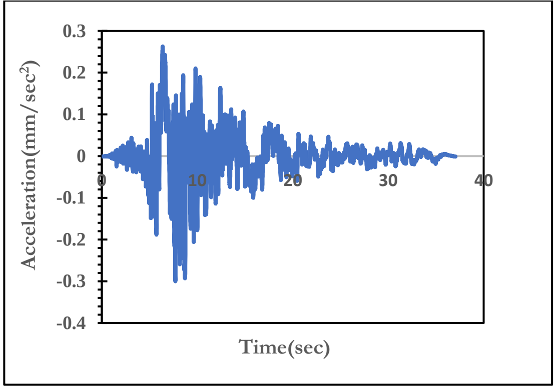

Figure (4): Acceleration time history of Imperial Valley-06, El- Centro - Array #10 station.

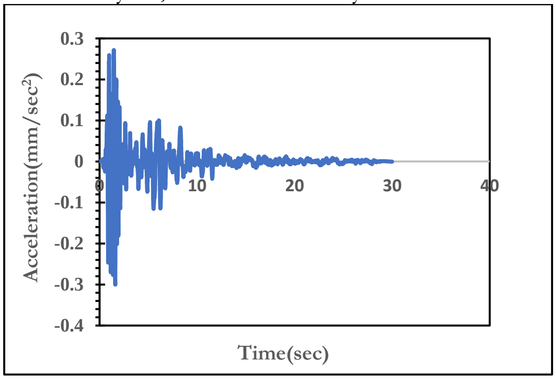

Figure (5): Acceleration time history of Morgan Hill, Gilroy Array- #6 station.

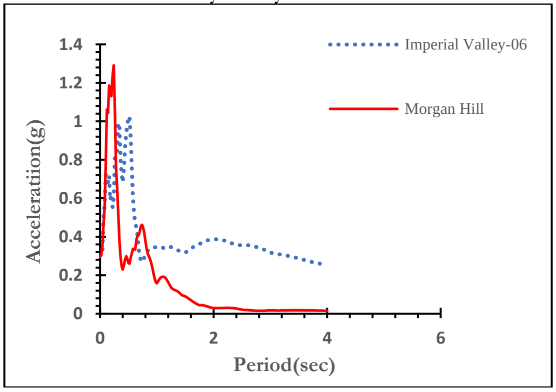

Figure (6): The acceleration response spectrum of Imperial Valley-06 Vs Morgan Hill earthquakes

4. The Pulse Period Effect (Tp)

The pulse period could be described as the period where the amplitude spectrum of the velocity ground motion reaches its highest value, so it is considered as one of the most important parameters that is interested to study. Thus, four records of near like pulse earthquakes that have various pulse period (Tp) were chosen in order to understand the impact of pulse period velocity on the construction's performance. The spectrum of the inelastic displacement that have a ductility factor of 3 was examined. The selected earthquakes presented in Table 1 are Coyote Lake, station Gilroy Array #2; Irpinia Italy-01, station Sturno (STN); Cape Mendocino, station Bunker Hill FAA; Darfield, New Zealand, station TPLC, and their pulse periods are 1.4, 3.27, 5.36, 8.932 sec respectively. For a comprehensive study, the selected near-fault earthquakes are organized into four series: Tp< 2 sec, 2 < Tp< 5 sec,5sec< Tp > 8 sec, Tp>8sec. Figure 7 illustrated the response spectrum of the inelastic displacement for the four series of a pulse-period. The findings revealed that peak displacement requirements are observed in a nearby of the pulse period limits. In addition, it is notice that there is an obvious increase in spectrum demand with longer pulse periods. The results are consistent with [21].

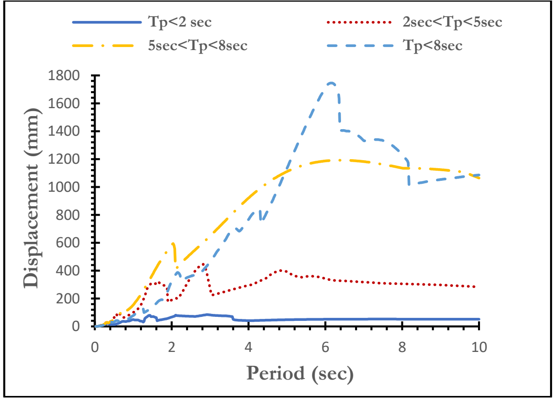

Figure (7): Response spectrum displacement for the four series of a pulse-period.

5. Fault Mechanism Effect on the (SDOF) System's Seismic Response

In this section, the faulting mechanism that affects the NFGM's response is examined. So, the strike-slip and dip-slip records are selected to distinguish this effect. When the relative movement of the tectonic plates occurs in a horizontal direction, the fault mechanism is called the strike-slip. However, the dip-slip fault develops when the tectonic plates shift vertically with respect to one another. Consequently, using the records listed in Table 1, which includes 6 dip-slip records and 11 strike-slip records. Where the maximum period was chosen as 4.00 sec, the SDOF elastic analysis is presented with a damping ratio ξ = 5%. Figure 8, Figure 9, and Figure 10 show the Response spectra of acceleration, velocity, and displacement of the average strike-slip and dip-slip records of near-fault earthquakes. Results show in the spectrum response of acceleration for both types (strike slip and dip slip) comparable results with a ratio of increase in the strike slip type at the maximum point of 11%. However, the spectrum response of velocity and displacement, at short vibration periods (T≤ 0.6sec) for both types (strike slip and dip slip), show comparable results while an increment is observed in the results of the dip-slip for vibration periods more than (0.6 sec). Except at the end of the displacement response spectrum, a dramatic drop is observed in the dip slip type with a ratio of 19.32%.The results are consistent with [22].

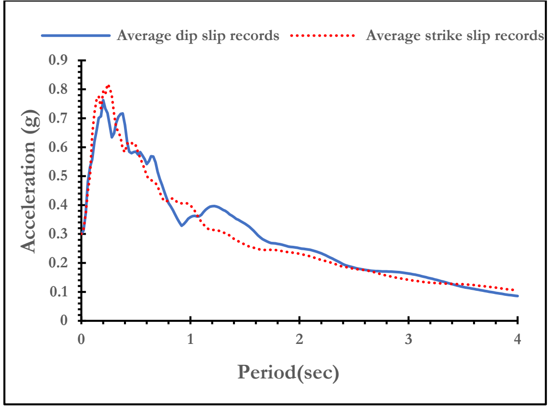

Figure (8): Response spectrum acceleration of the average strike-slip and dip-slip records.

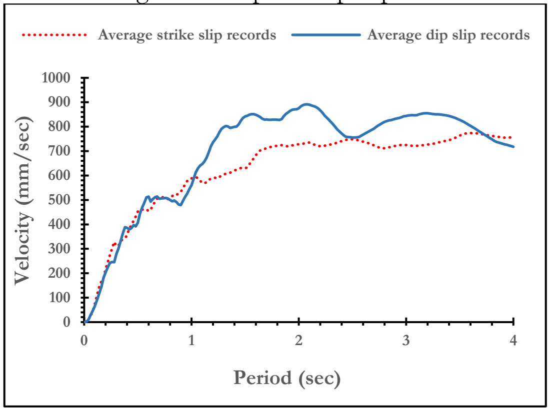

Figure (9): Response spectrum velocity of the average strike-slip and dip-slip records.

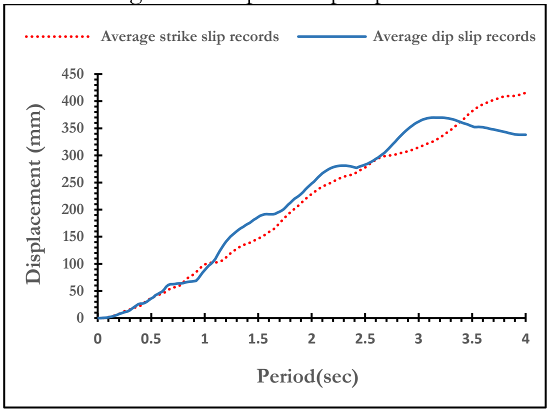

Figure (10): Response spectrum displacement of the average strike-slip and dip-slip records.

6. Conclusion:

The seismic reaction of single degree of freedom systems exposed to near fault like pulse records were assessed in this paper since a large number of structures which situated near faults may experience this type of earthquakes. The following points could be list in order to summarize the essential findings based on the selected properties of the applied earthquakes.

1. When studying the impact of the shear wave velocity (VS30), results show that the ground motion with a higher value of (VS30) provides an acceleration response higher than that of the lower value of (VS30), with ratio increase about 23% at the peak. In another words, the soil type D (Stiff Soil) gives an acceleration response lower than that of the soil type C (Dense soil/soft soil).
2. The findings revealed that the peak displacement requirements are observed in a nearby of the pulse period limits.
3. It is noticed that there is an obvious increase in spectrum demand with longer pulse periods.
4. Results show in the spectrum response of acceleration for both types (strike slip and dip slip) comparable results with a ratio of increase in the strike slip type at the maximum point of 11%.
5. The spectrum response of velocity and displacement, at short vibration periods (T≤ 0.6sec) for both types (strike slip and dip slip), show comparable results while an increment is observed in the results of the dip-slip for vibration periods more than (0.6 sec). Except at the end of the displacement response spectrum, a dramatic drop is observed in the dip slip type with a ratio of 19.32%.

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