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Study on the Seismic Response of Slope under Pulse-Like Ground Motion

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***Abstract*—**Near-fault ground motions with velocity pulses are considered to cause significant damage to structures or slopes compared to ordinary ground motions without velocity pulses. The double pulsed pulse-like ground motion is well known to be stronger than the single pulse. This research has numerically justified this perspective by studying the dynamic response of a homogeneous rock slope subjected to four pulse-like and two non-pulse-like ground motions using the Fast Lagrangian Analysis of Continua in 3 Dimensions (FLAC3D) software. Two of the pulse-like ground motions just have a single pulse. The results show that near-fault ground motions with velocity pulses can cause a higher dynamic response than regular ground motions. The amplification of the peak ground acceleration (PGA) in horizontal direction increases with the increase of the slope elevation. The seismic response of the slope under double pulse ground motion is stronger than that of the single pulse ground motion. The PGV amplification factor under the effect of the non-pulse-like records is also smaller than those under the pulse-like records. The velocity pulse strengthens the earthquake damage to the slope, which results in producing a stronger dynamic response.

***Keywords*—**Velocity pulses, dynamic response, PGV magnification effect, elevation effect, double pulse.

I. INTRODUCTION

EARTHQUAKE-induced disasters often cause countless injuries and fatalities, leading to significant economic losses. Some catastrophic earthquake-induced disasters include the Chi-Chi earthquake, which triggered about 9000 landslides, [1], the Wenchuan earthquake that triggered 15,000 geohazards, including landslides [2], and the Guatemala earthquake that triggered 10,000 landslides [3]-[5]. For earthquake-induced landslides, many researchers have studied the response of slopes and structures to ground motion and their subsequent displacement [3], [5]-[8]. Earthquakes could be pulse-like or non-pulse-like depending on the distance to earthquake epicentre and velocity pulses [9].

The rapture directivity, velocity pulse size, displacements, and fling-effect characteristics make pulse-like ground motion more dangerous than non-pulse-like ground motion. Pulse-like ground motion's hazardous nature has made its consideration in structural design necessary, attracting many researchers to study the response of structures to the pulse-like ground motion [11], [12]. However, only a few studies highlight the effect of the pulse-like ground motion on the dynamic response of rock slope under pulse-like ground motion [13]. This paper, therefore, presents a comparison of double pulsed pulse-like ground motion, single pulsed pulse-like ground motion, and ordinary ground motion's effect on the dynamic response of homogeneous rock slope under earthquake ground motion. The fling and forward directivity incident wave are analysed using a finite-difference method in FLAC3D. The amplification and elevation effect are considered for computing the slopes amplification factors and dynamic response. Six ground motion records containing four pulse-like ground motions (two having a single pulse and two ordinary ground motions records) are used to observe the behaviour of homogeneous rock slopes under earthquake ground motions and their dynamic response.

II. CHARACTERISTICS OF PULSE-LIKE GROUND MOTION

Earthquake ground motions have unique characteristics in terms of source, distance, direction, and magnitude. These characteristics define the ground motions as being near fault or far fault ground motion. The directivity effect, fling step, and pulse-like nature of the near fault ground motion imposes higher damages on structures making it more dangerous than far fault ground motions [14]. The directivity effect occurs when the velocity of the fault rupture is closer to the shear wave's velocity, leading to long-velocity pulses. These pulses are stronger when the rapture propagation is towards the site [15]. The fling step results from the evolution of pulse-like ground motion and constitutes large amplitudes velocity pulses with a monotonic step in the displacement time history which typically arises in strike-slip faults in the direction parallel to the strike [15]. Near fault ground motion could as well be pulse like or non-pulse-like. Structural response to pulse-like ground motion is primarily different and dangerous than the non-pulse like ground motions [9], [16].

The unique characteristics of the pulse-like include high amplitudes, long duration velocity pulses, and the direction of the rupture propagation. These characteristics of the pulse-like ground motions make it dangerous to the stability of structures [17]. Reference [6] pointed out that, near-fault pulse-like ground motion increases the displacement and damage response of structures compared to the near-fault non pulse-like ground motion. Fig. 1 shows the sample acceleration, velocity and displacement of double pulse, pulse like, single pulse and ordinary ground motions.

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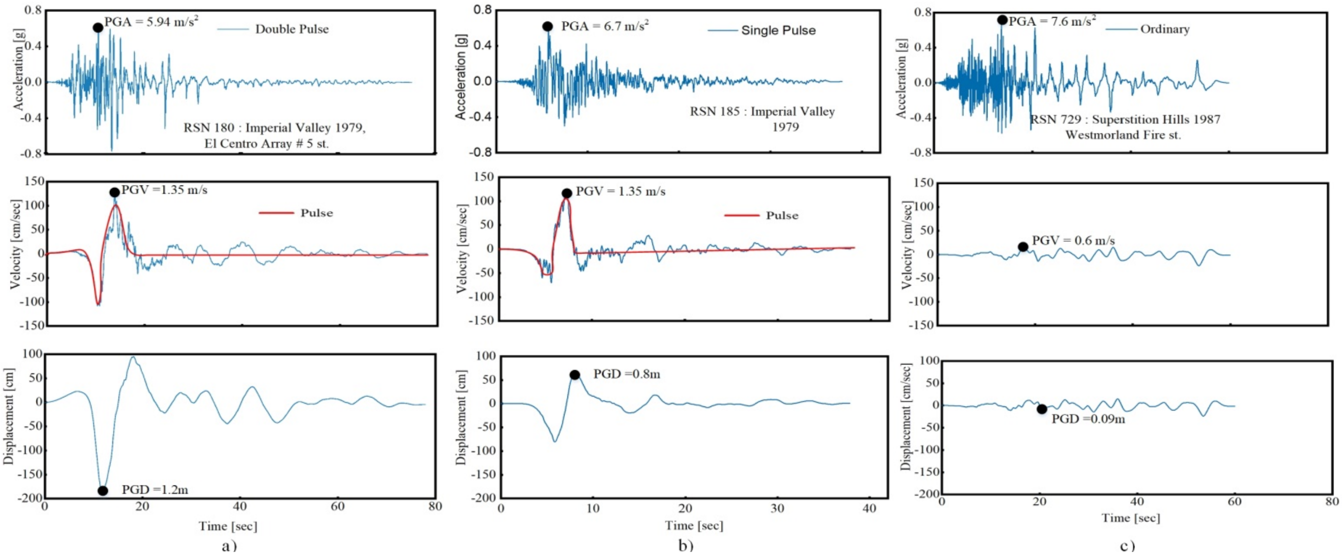


a) b) c)

Fig. 1 Sample of acceleration, velocity, and displacement for (a) double pulse pulse-like ground motion recorded, (b) single pulse pulse-like ground motion, (c) ordinary ground motion

TABLE I
ROCK PROPERTIES

Density ρ (kg/m^3)	Poisson ratio μ	Elastic modulus *E*(MPa)	Friction angle *φ*(°)	Cohesive force *c*(kPa)	Extension strength (MPa)	Tensile strength (N/M^2)
2000	0.36	455	45	5.7	5	1e7

III. NUMERICAL SIMULATION OF SLOPE DYNAMIC RESPONSE

A. Slope Material

The material properties of the homogeneous rock slope model used for this study include cohesion, c, frictional angle, ϕ, and unit weight, γ. The slope model is designed as an isotropic model adopting the Drager-Prager constitutive relationship having a tensile failure acting vertically and earthquake loading applied at the base. The physical and mechanical parameters of the rock adopted in numerical simulation are shown in Table I. A mesh size of 1 m for finite difference method dynamic analysis is used [6].

B. Model Size

Finite Difference software FLAC3D is used to perform the numerical analysis of a homogeneous isotropic rock slope. The rock mass adopted for this study is mainly a hard rock having the same properties as limestone and carbonate rocks. The Poisson's ratio V = 0.36 and mass density ρ = 2.13 mg/m^3. Fig. 2 is an illustration of the slope size having a height, H. The distance from the top to the right boundary is equivalent to the toe to the left boundary. The total height of the slope from top to bottom is twice its H with a 45-degree angle conforming to standard [6].

The slope has seven monitoring points ranging from Q1 to Q7 where the slope height is used as a reference, with a 2 Bm interval. A displacement constraint condition is applied at the bottom of the slope to produce quiet boundaries at both ends. The stress time history from the earthquake loadings in Table II is used for load input, and a 0.157 local damping coefficient is used [18].

IV. GROUND MOTION RECORDS USED

This study uses six forward-directive natural earthquake ground motion records with magnitude (*Mw*) above 6.0 (Table II). The records are grouped into double pulsed pulse-like, single pulsed pulse-like and ordinary earthquake ground motion. These records are taken from the PEER ground motion data [18]. Selection of the pulse-like ground motions involved the extraction of velocity pulses before establishing a relationship between the double pulsed pulse-like, single pulse pulse-like, and non-pulse-like ground motions and their dynamic response [10]. Amplitude modulation is done to adjust the accelerations of the ordinary ground motions to the level of the pulse-like ground motions to eliminate all biases because the research aims to determine the influence of the velocity pulse (Fig. 3) on the slope rather than the amplitudes (Fig. 4).

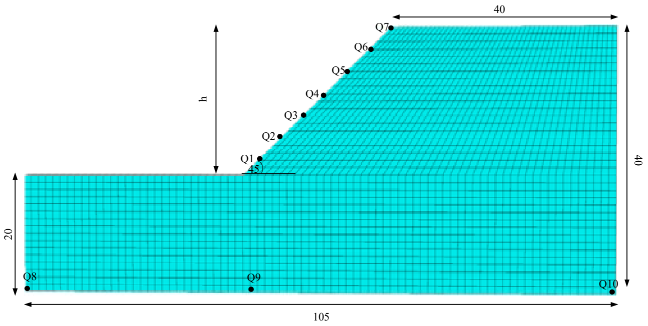


Fig. 2 Slope model

TABLE II
PROPERTIES GROUND MOTION RECORDS CONSIDERED IN THIS STUDY

RSN	Earthquake	Station	EpiD (km)	RjB Distance (km)	Mw	PGA (cm/s^2)	PGV (cm/s^2)	Ground Motion
179	Imperial Valley 1979	El Centro Array #4	27.13	4.9	6.53	292	16.864	Double Pulse
180	Imperial Valley 1979	El Centro Array #5	29.53	1.8	6.53	594	39.536	Double Pulse
185	Imperial Valley 1979	Holtville post office	19.8	5.4	6.53	257	10	Single Pulse
1510	Chi-Chi 1999	TCU075	20.77	0.9	7.62	228	50.9	Single Pulse
729	Superstition Hill 1987	Westland Fire st.	29.41	23.9	6.54	402	6.15	Ordinary
963	Northridge 1994	Carson Water st.	50.30	45.4	6.69	217	12.3	Ordinary

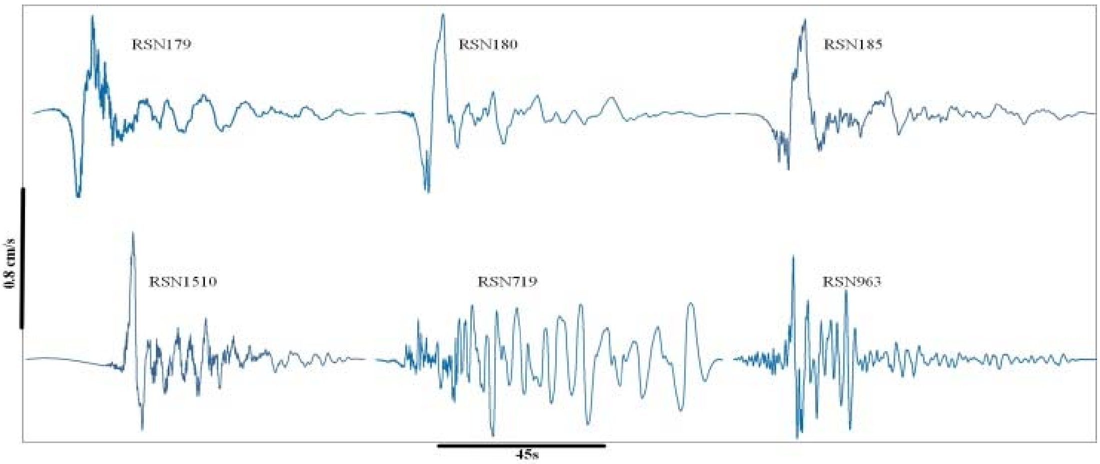


Fig. 3 Velocity time history of pulse like and ordinary ground motion

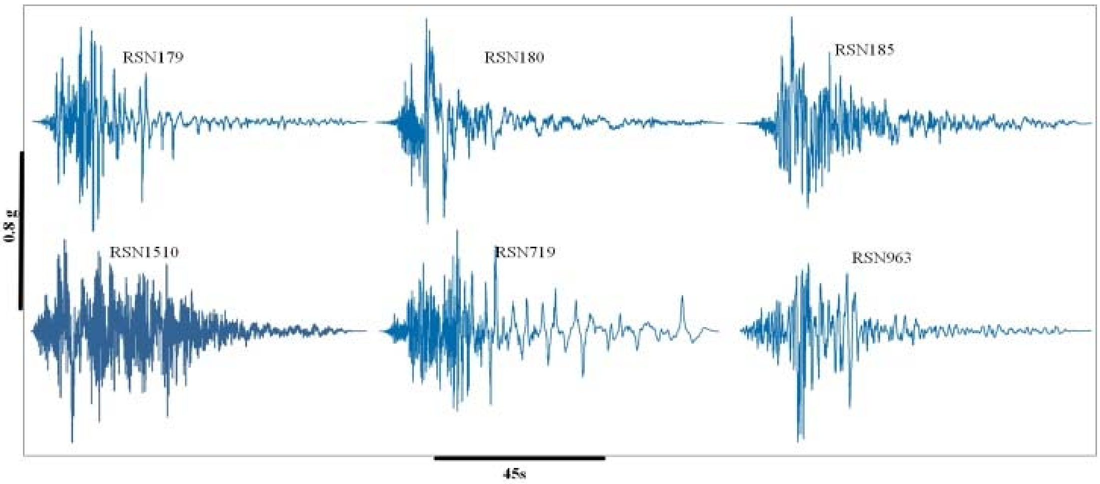


Fig. 4 Acceleration time history of pulse-like and ordinary ground motion

V. SLOPE DYNAMIC RESPONSE

The acceleration, velocity, and displacement are often used to determine the seismic response of the slope under earthquake loading [19]. The dynamic response is closely related to acceleration, making it a primary consideration factor for slope instability [20]. The dynamic behaviour of slopes under earthquake loadings has been studied by some researchers [19]. Dynamic response of slope has elevation amplification effect which means the slope surfaces PGA and PGV amplification coefficients increase with the increase of the elevation [21] (Fig. 5).

A. Acceleration Dynamic Response

Earthquake initial seismic force is closely related to acceleration, which results from slope failure [17], [20]. The acceleration response on the slope surfaces is computed by comparing the effect of the seismic energy around the slope under dynamic response. PGA is directly correlated with the height of the slope, while acceleration is the leading cause of instability. Therefore, the PGA response at all points on the slopes surface (Q1, Q2, Q3, Q4, Q5, Q6, and Q7) is determined.

The acceleration law is exploited by introducing a PGA magnification effect, which is used to determine the PGA amplification effect (PGA_{max}) for each of the seven points on the slope surface. The PGA amplification change rule with the slope height (h/H) is determined (Fig. 5).

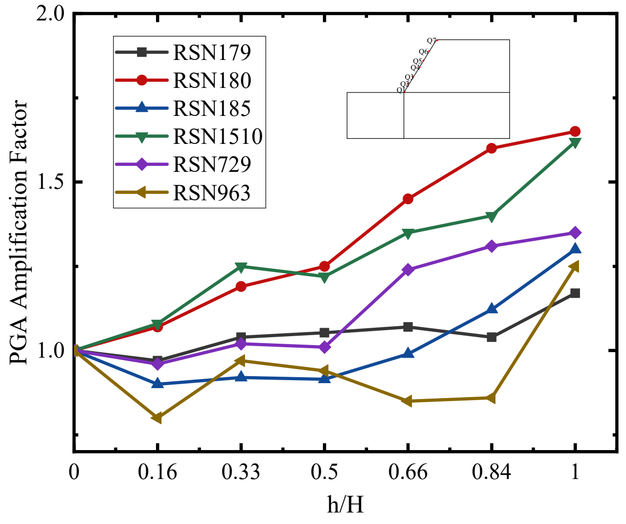


Fig. 5 Variations in PGA amplification factor for each monitoring point of the slope surface under horizontal earthquake loading containing the double pulse, single pulse and ordinary ground motions

Considering the slope structure in Fig. 2, under natural earthquake loading RSN 179, PGA_{max} at the highest point on the slope surface (Q7) is 1.72, while the PGA_{max} at the lowest point (Q1) is 0.7, meaning slope PGA response increases with an increase in the height of the slope confirming [21].

B. Velocity Dynamic Response

The Peak Ground Velocity (PGV) response is computed to determine the slopes speed relation. Like the PGA application effect, the PGV amplification effect (PGVmax) also has an elevation effect. It is computed as the ratio of the measured maximum PGV at each point of the slope surface to the measured maximum PGV at the toe of the slope after the dynamic analysis (Fig. 6).

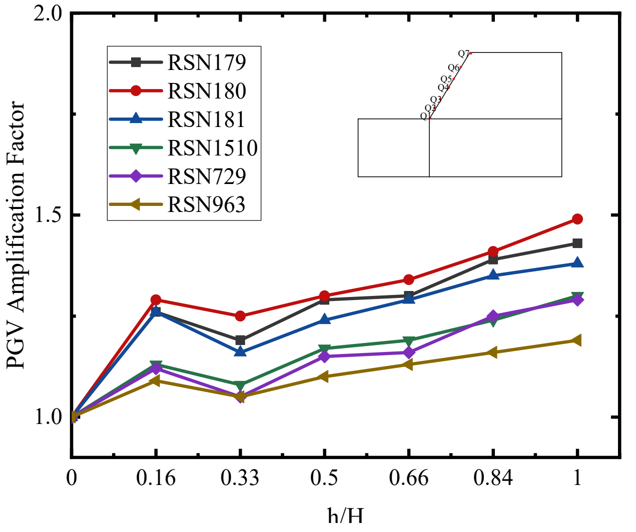
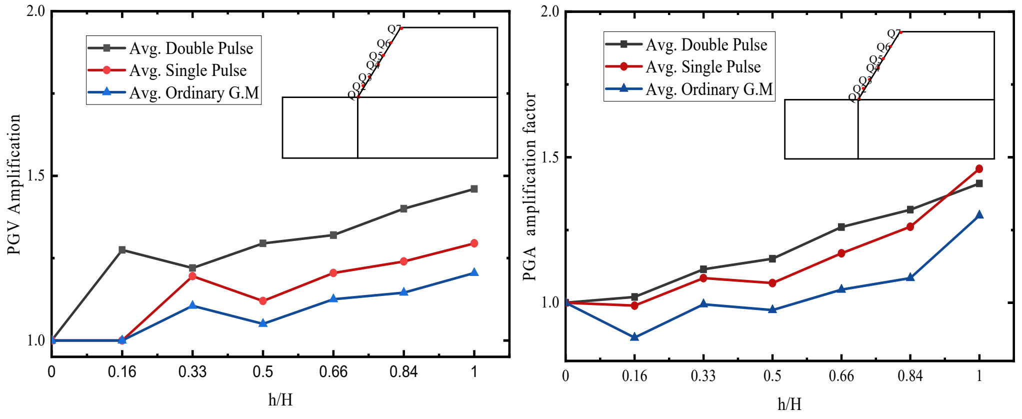


Fig. 6 Variations in PGV amplification factor for each monitoring point of the slope surface under horizontal earthquake loading containing the double pulse, single pulse and ordinary ground motions



a

b

Fig. 7 (a). Average PGV amplification factors in the horizontal direction for double pulsed pulse-like, single pulsed pulse-like and ordinary earthquake ground motions. (b). Average PGA amplification factors in the horizontal direction for double pulsed pulse-like, single pulsed pulse-like and ordinary earthquake ground motions

VI. COMPARISON

The average PGA and PGV responses for double pulse pulse-like, single pulse pulse-like, and ordinary earthquake ground motion are compared (see Fig. 7). The double pulse is seen to produce a stronger PGA and PGV dynamic response.

VII. CONCLUSIONS

In this study, the dynamic response of a homogeneous rock slope subjected to natural earthquake ground motion is numerically analysed using the numerical FLAC3D software.

Two recorded double pulsed pulsed-like, two single pulsed pulse-like, and two ordinary earthquake ground motions with magnitudes above 6.0 are used for the numerical simulation.

Some conclusions can be obtained as follows:

1. PGV and PGA amplification effects of slope structures exposed to earthquake ground motions have an elevation effect. This means their response values increase with the increase in slope height because the PGA amplification factor of a rock slope is generally positively correlated with the height of the slope under earthquake loadings.
2. The dynamic heights increment of the PGA amplification factor becomes more rapid as it reaches the middle-upper part of the slope to the maximum amplitude at the crest. This, resulting from the fact that seismic waves spread upwards and closer to the shoulder of the slope than other parts due to seismic waves overlap.
3. Double pulsed pulse-like ground motions have higher PGV responses than single pulsed pulse-like ground motions, which also have higher responses than ordinary ground motions. This indicates that the impulse nature of pulse-like ground motions makes them fierce inducers of earthquake hazards compared to ordinary ground motions (Fig. 6)
4. PGA amplification response can be the same for all ground motion types. Still, it can never be the same for PGV amplification values, which indicates that velocity pulses are the primary hazards associated with earthquake ground motion rather accelerations.

Per this study, pulse-like earthquake ground motions significantly affect the dynamic response and subsequent failure of slopes due to its impulsive effects. Double pulsed pulse-like ground motions cause more havoc than single pulse, which also cause more havoc than the ordinary ground motions and can cause more damage to the slope materials.

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