COMPARISON OF MULTI-DIRECTIONAL SHAKING OF SLOPES USING DIFFERENT NUMERICAL TOOLS

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Abstract

Earthquake response analysis of slopes is often performed using 1-D and 2-D models with one component of earthquake shaking applied in the downslope direction. However, several studies, both numerically and experimentally, have demonstrated the importance of multidirectional shaking. Therefore, there is a need to understand better the effect of multidirectional shaking on slope stability and how it can be incorporated in a simple yet effective manner with traditional slope stability analyses. In this paper we perform 3-D dynamic slope stability analyses in several different numerical programs to validate the results of earlier studies, we investigate the effect of modelling uncertainty on slope displacement due to multidirectional shaking, and we evaluate which program(s) to use in a future parametric study. Specifically, we compare results of multidirectional shaking on slopes calculated using the finite element programs OpenSees and Plaxis, and the finite difference program FLAC. We use one slope profile with slope angle of 15 degrees and four two-component ground motions from active crustal regions. The results show that regardless of ground motion or numerical program, when two ground motion components are applied, one in the downslope and one in the cross-slope direction, the predicted displacements are larger compared to when only one component is applied in the downslope direction. However, in some cases, ground motion orientation and modelling uncertainty are greater than the difference between analyses with one or two components. Nevertheless, the general trends between programs are similar and none of the programs shows a consistent high or low bias in its results.

Keywords: Slope; Earthquake response; Multi-directional shaking; Displacement equations

1. Introduction

Earthquake induced landslides are a major hazard in many areas of the world. As a result, there are numerous different methods to assess the displacements of a slope due to earthquake shaking. These methods vary in complexity from equations based on simplified slope and ground motion parameters (e.g. Jibson, 2007 [1]; Saygili and Rathje, 2008 [2]; Bray et al., 2018 [3]), to the Newmark sliding block model that incorporates the full acceleration time series but assumes the failing soil acts as a rigid body (Newmark, 1965 [4]), to numerical simulations that incorporate the full slope geometry and acceleration time series. The first two methods can only accommodate one component of a ground motion, and it is common practice to use only one component when performing numerical simulations even in three dimensions (Kaynia, 2018 [5]). The basic assumption in these analyses is that the main response occurs in the direction of shaking in the plane of the model, and the earthquake excitation in the other directions is negligible. This assumption helps constrain the complexity of the problem and allows sensitivity studies with moderate computational efforts. However, this assumption has been found to be unconservative (Carlton and Kaynia 2016 [6]; Kayen, 2017 [7]). Therefore, there is a need to understand better the effect of multidirectional shaking on slope stability and how it can be incorporated in a simple yet effective manner with traditional slope stability analyses.

Most research related to multidirectional shaking is primarily concerned with liquefaction analyses or site response analyses for level ground conditions. Several laboratory and centrifuge studies have shown that multidirectional shaking causes an increase in settlement and excess pore pressure compared to unidirectional shaking (Pyke et al., 1975 [8]; Seed et al., 1978 [9]; Kammerer et al., 2003 [10]; Su and Li, 2003 [11]; Ng et al., 2004 [12]; Stewart and Yee, 2012 [13]; El Shamy and Abdelhamid, 2017 [14]). More recently, several researchers have investigated the effect of multidirectional shaking on site response analyses for level ground (Stewart et al. 2008 [15]; Carter et al., 2014 [16]; Bolisetti et al., 2014 [17]; Motamed et al., 2016 [18]). These studies found that using two components of a ground motion gave results that more closely matched the measured response. This is due in part to the redistribution of seismic wave energy when movement can occur in both directions simultaneously (Stewart et al., 2008 [15]).

Despite the large body of research related to multidirectional shaking for liquefaction and site response analyses, there is relatively little research related to the effect of multidirectional shaking on slopes. Rutherford (2012) [19] developed a multi-directional direct simple shear device and found that shearing in a figure eight pattern developed more permanent deformations in fewer cycles than both cyclic and circular tests, and that the shear strains accumulated in the same direction as the initial horizontal shear stresses, independent of the orientation of the cyclic loading. Anantanavanich et al. (2012) [20] and Yang et al. (2019) [21] developed constitutive models explicitly for use in multidirectional earthquake shaking. Carlton and Kaynia (2016) [6] conducted 27 three-dimensional seismic slope stability analyses in Plaxis3D, applying one, two, and three ground motion components. They found that accounting for two horizontal components rather than just one increases the predicted total displacements on the slope by 25% to 50%. Kayen (2017) [7] performed analyses for gently sloping marine slopes using a modified compliant multidirectional Newmark sliding block model. He found that adding the second component across the slope always gave a larger and more accurate shear stress vector and increased downslope displacements.

In this paper, we present the results of benchmarking analyses to compare the results of multidirectional shaking on slopes calculated using the programs OpenSees [22], Plaxis [23], and FLAC [24]. The purpose of the benchmarking analyses is to validate the results of Carlton and Kaynia (2016) [6] in other numerical programs, to investigate the effect of modelling uncertainty on slope displacement due to multidirectional shaking, and to evaluate which program(s) to use in a future parametric study. The main goal of this research is to develop a model that uses simplified slope and ground motion parameters to estimate the change in permanent displacements between analyses that use only one horizontal component and analyses that use two horizontal components. The benchmarking analyses are an important first step in this research.

2. Methodology

2.1. General

We performed three-dimensional seismic slope stability analyses in the finite element programs OpenSees and Plaxis, and the finite difference program FLAC. We used the same soil models, soil properties, slope angle, and ground motions in all three programs. However, the programs differ in how they model the geometry of the system and the dynamic boundary conditions.

The slope used for the benchmarking analyses has a slope angle of 15 degrees, slope height of 13.4 meters, and 55 meters of soil beneath the toe of the slope over bedrock. The soil profile is representative of a typical soft, cohesive soil site found in offshore environments. Figure 1 shows the undrained shear strength and shear wave velocity of the soil versus meters below sea floor (mbsf). All three programs use the Mohr-Coulomb (or equivalent) constitutive model. The total unit weight of the clay is 18 kN/m^3.

We used four two-component ground motions taken from the PEER NGA West 2 online database [25]. Table 1 lists the metadata for each ground motion, where RSN is the record sequence number assigned by PEER, M_w is the moment magnitude, R_{rup} is the source to site rupture distance, and Vs_{30} is the time averaged shear wave velocity over the top 30 meters of the recording station. Table 2 lists ground motion parameters for each component, where Comp is the component, Comp ID is the identification assigned for this paper, PGA is peak ground acceleration, PGV is peak ground velocity, PGD is peak ground displacement, $D_{5\text{-}75}$ is significant duration, Tm is mean period and Ia is Arias intensity. Figure 2 shows the eight acceleration time series. For each ground motion we performed four analyses. We performed one analyses for each component on its own in the downslope (x) direction, and then with the other component in the cross-slope (y) direction. Specifically, the four analysis cases are 1) component A in the x direction; 2) component A in the x direction and component B in the y direction; 3) component B in the x direction; 4) component B in the x direction and component A in the y direction. The following sections discuss briefly the specific features of each program.

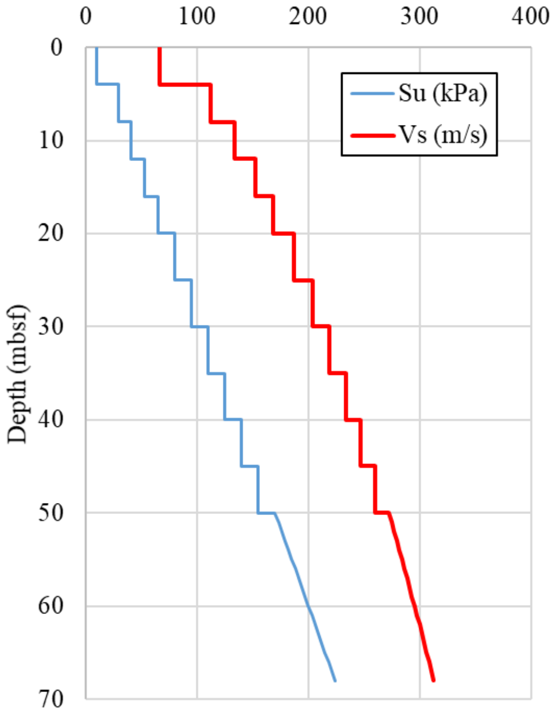

Fig. 1 – Site profile for multidirectional shaking analysis

Table 1 – Metadata for ground motions used in the analyses

RSN	**Earthquake Name**	**Year**	**Station Name**	**M_w**	**R_{rup} (km)**	**V_{S30} (m/sec)**
80	San Fernando	1971	Pasadena - Old Seismo Lab	6.61	21.5	969
765	Loma Prieta	1989	Gilroy Array #1	6.93	9.64	1428
8165	Duzce	1999	IRIGM 496	7.14	4.21	760
5618	Iwate	2008	IWT010	6.9	16.3	826

Table 2 – Ground motion parameters for each ground motion component used in the analyses

RSN	**Comp**	**Comp ID**	**PGA (g)**	**PGV (cm/s)**	**PGD (cm)**	**D_{5-75} (s)**	**Tm (s)**	**Ia (m/s)**
80	180	A	0.086	5.95	0.61	5.7	0.27	0.11
80	270	B	0.199	13.36	1.29	3.3	0.32	0.34
765	0	A	0.415	32.72	8.85	2.0	0.30	1.04
765	90	B	0.448	39.59	8.55	1.3	0.40	1.66
5618	EW	A	0.276	24.22	8.16	7.6	0.56	1.29
5618	NS	B	0.204	23.22	6.82	9.1	0.50	1.26
8165	EW	A	0.750	37.79	12.03	9.9	0.26	6.49
8165	NS	B	1.046	51.23	13.68	10.2	0.25	13.31

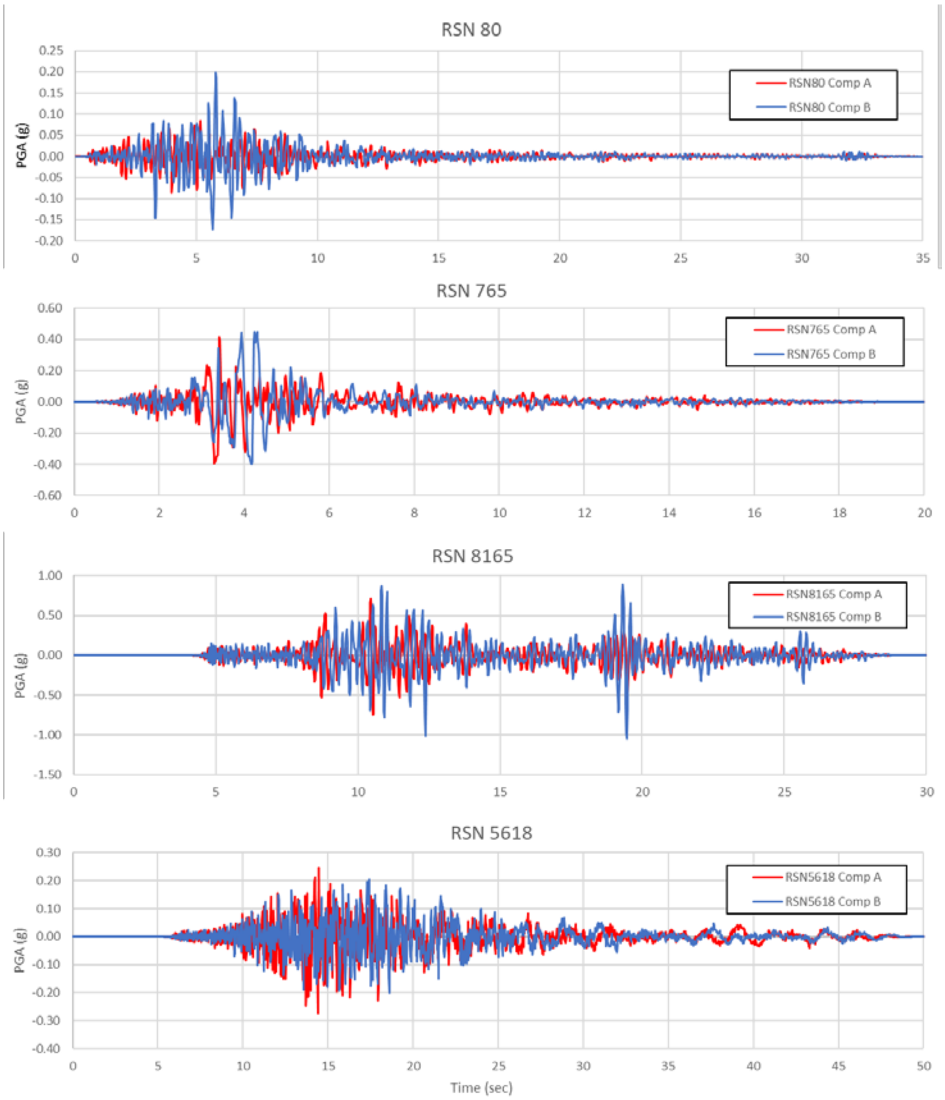

Fig. 2 – Acceleration time series used in the slope stability analyses

2.2. Analyses in Plaxis

Figure 3 shows the three-dimensional model in Plaxis. The model is 250 meters wide, 300 meters long, 68.4 meters tall at the top of the slope, and 55 meters tall at the foot of the slope. The slope itself has a slope angle of 15 degrees, is 13.4 meters tall and 52 meters long. The model consists of 86829 soil elements, with minimum element size of 3 meters, and average element size of 9 meters. Because we are only interested in displacements, which are dominated by long period energy, we allowed the model to have large elements to reduce computation time. We initially tried to use free field boundary conditions on the sides, which would have allowed for a much smaller model. However, we encountered an error when free field boundary conditions are used on both sides of a 3D model. Plaxis is currently fixing this error (Plaxis, personal communication, 12 December 2019). As a result, we used a large model with viscous side boundaries and a compliant base boundary instead. We calibrated the 3D model against a 2D model for the case with only one earthquake component applied downslope. We adjusted the 3D model size and element size until we achieved a reasonable match with the 2D model results. We take results only from a point in the exact centre of the 3D model to reduce boundary effects. Calculation time for each model ranged from 4 to 8 hours depending on the duration of the ground motion.

We used the built-in Mohr-Coulomb model available in Plaxis with conventional Rayleigh damping. The Rayleigh damping has target frequencies of 1 Hz and 5 Hz, and damping ratios of 6%, 3% and 1% for depths of 0 to 20 m, 21 to 50 m, and >50 m, respectively.

2.3. Analyses in OpenSees

We implemented a simplified model in OpenSees to simulate an infinite slope. The model consists of a single vertical column of 3D brick elements that are supported vertically at the base. So-called "tied" boundary conditions [26] are applied in both horizontal directions at each elevation in the model to constrain the column to deform as a shear beam. A viscous damper (dashpot) [27] is applied at the base to simulate the radiation of energy into the underlying infinite elastic medium, and the earthquake loading is applied to the model at this location according to the method proposed by Joyner and Chen [28].

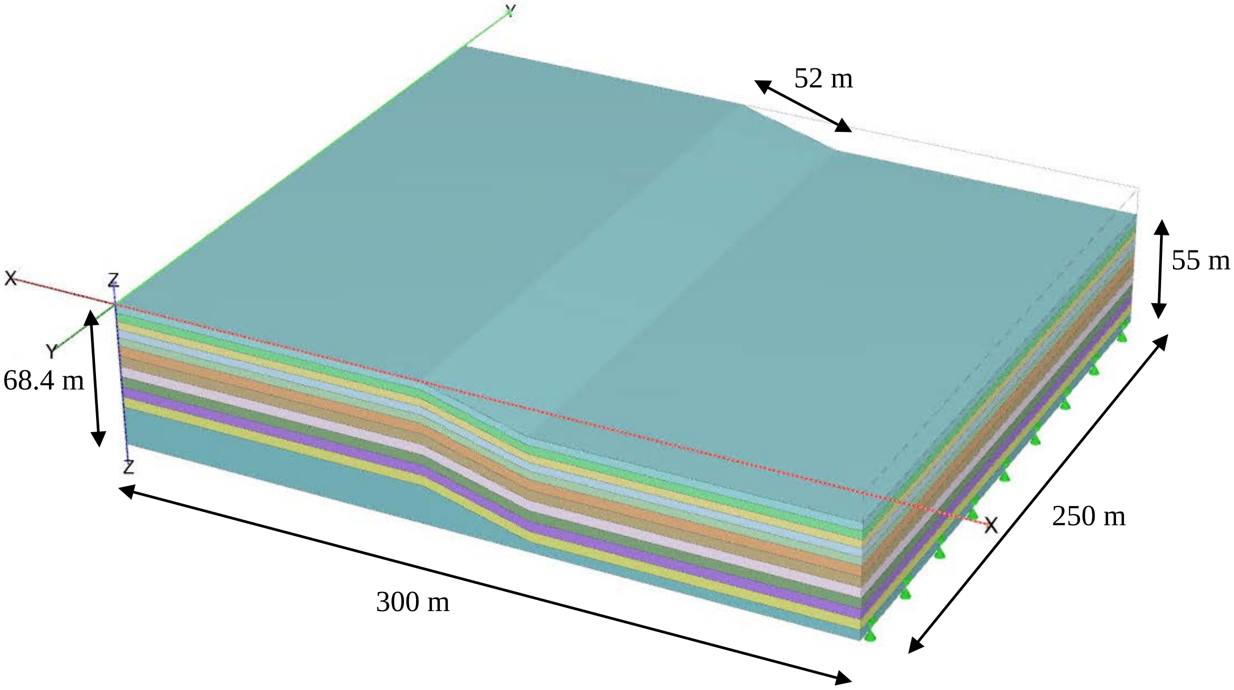

Fig. 3 – Three-dimensional slope model in Plaxis

To model the inclination of the slope, gravity forces are applied with components in the vertical (z) and downslope (x) directions according to the angle of the slope. This generates static shear forces in the column that simulates the infinite slope. To ensure that the analysis model is comparable to the cases simulated in the full 3D analyses in Plaxis and FLAC, where the height of the slope is 13.4m, inclined gravity forces are just applied to the top 13.4 meters, and "normal" vertical gravity forces are applied to the part of the column below this.

The finite element model consists of sixty-nine 3D single-integration point brick elements, each with a height of 1m. The material is modelled using the PressureIndependMultiYield material in OpenSees which is given model properties consistent with elastic-perfectly plastic behaviour following the Mohr-Coulomb material model. Conventional Rayleigh damping is specified at target frequencies of 1 Hz and 5 Hz with a damping ratio of 3% for the whole profile. Due to the small size of the OpenSees model, it runs very fast, with typical run times of 10 seconds to 2 minutes depending on ground motion duration.

2.4. Analyses in FLAC

The finite difference model in FLAC had the same geometry as the Plaxis model (Figure 3). For accurate representation of wave transmission through the model, the maximum dimension for each element in the FLAC model must be less than one-tenth of the earthquake wavelength (Kuhlemeyer and Lysmer, 1973 [29]). We therefore set the size of the FLAC zones to 5.00 m. We used free field boundary conditions in FLAC for the lateral boundaries, and a compliant boundary at the base. We specified the input motions as shear stresses to be consistent with the compliant base conditions. We estimated the input shear stress according to the method of Joyner and Chen [27]. The computation time for each analysis was about 8 days.

3. Results of seismic slope stability analyses

In this study we focus on the absolute total displacements at the soil surface for a point in the exact centre of the model in the middle of the slope. This section presents the results for each program. Section 4 compares the results of each program.

Figure 4 shows the total displacements of the entire slope for when RSN 765 Comp B is applied in the downslope direction in Plaxis. Due to the effect of the viscous boundaries, the displacements at the lateral edges of the model are less than in the middle. As a result, we only compare displacements at the center of the model, where boundary effects are least. For this case, the total permanent displacement at the center of the model at the soil surface is 13 cm.

Figure 5 shows the total displacement versus time for all the Plaxis analyses. There is one plot per earthquake and each plot contains the four different analysis cases. The results show that when the second component is added in the cross-slope direction (y), the displacements increase. However, there is a large difference in displacements depending on which component is applied in the downslope direction and which in the cross-slope direction. This is highlighted by the fact that analyses for RSN 80 and RSN 765 have larger displacements for when one component is applied downslope than when that component is applied across the slope and the other component is applied downslope. Therefore, careful consideration should be given to the orientation of the ground motion when conducting seismic slope stability analyses (Carlton et al., 2016 [30]). The results for RSN 80 when component A is applied downslope appear to have a drift in the results. This is mainly due to displacement in the vertical direction. This phenomenon was also seen in the FLAC analyses. Figure 5 also shows that the difference in displacements between one and two components occurs during the strongest part of shaking.

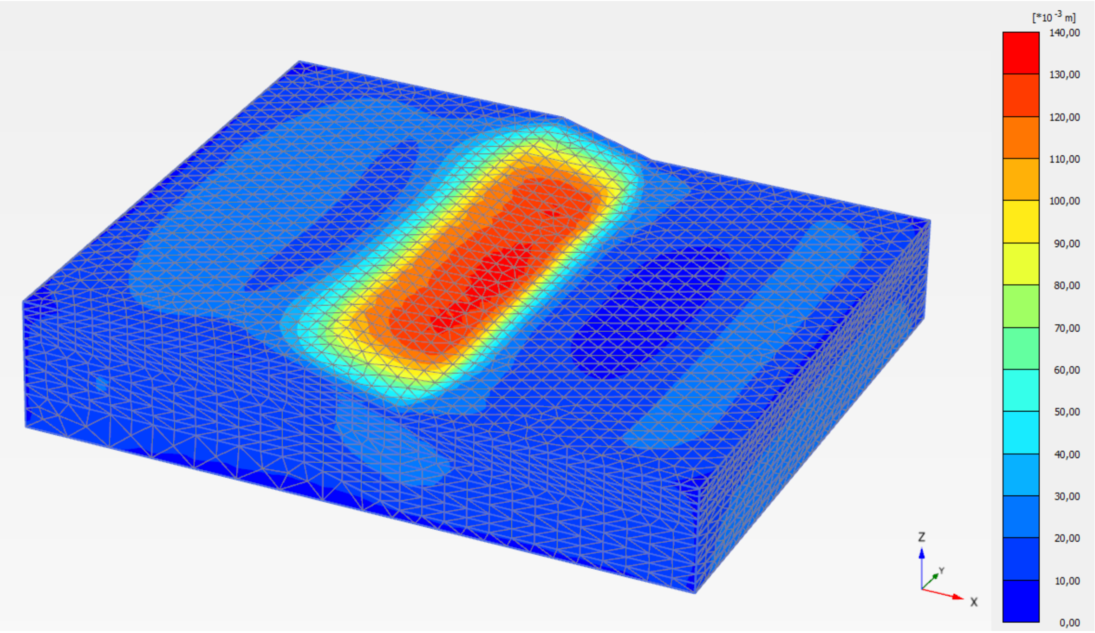

Fig. 4 – Permanent total displacements for RSN 765 Comp B applied in the downslope (x) direction in Plaxis.

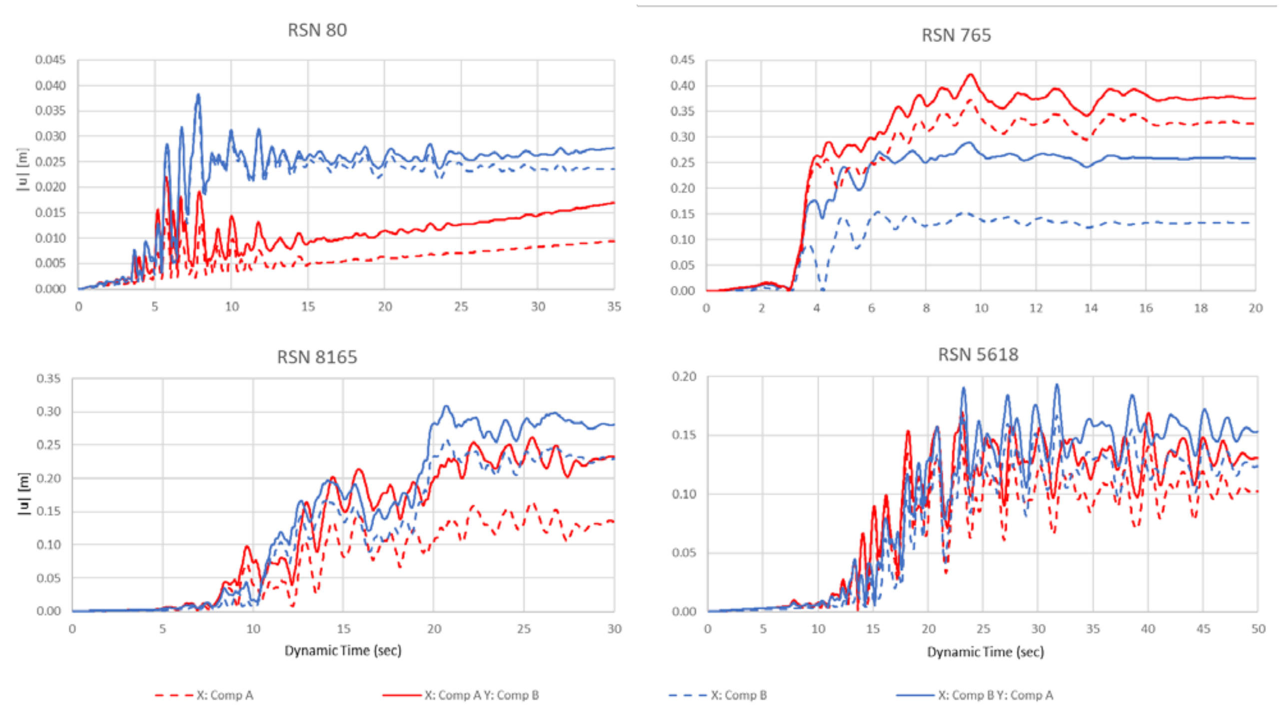

Fig. 5 – Total displacement versus time for the four earthquakes in Plaxis. The four analyses include each component on its own in the downslope direction (dashed lines) and with the other component in the cross-slope direction (solid lines).

Table 3, Table 4 and Table 5 list the total displacements at the end of shaking for results in Plaxis, OpenSees and FLAC, respectively. For all analyses, the displacements increase when a second component is added in the cross-slope direction. The increase in displacements due to adding a second component vary from 5% to 286%, depending on the program used and which ground motion component is applied downslope. These results confirm the work of Carlton and Kaynia 2016 [6], and show that an increase in displacements is not program, slope or ground motion specific. Due to the long run time in FLAC, results for RSN 5618 were not available in time for this paper and therefore are not presented for this particular earthquake.

Comparing Table 2 with Table 3, Table 4 and Table 5 also shows that the component with the larger PGA does not always give larger displacements. This is because PGA is affected by high frequency energy whereas slope displacements are more affected by low frequency energy. There is no direct correlation between any single parameter in Table 2 and which component gives the most displacement. This is because slope displacement is affected by several different ground motion properties such as duration, intensity, and frequency content (Bray et al., 2018 [3]).

Table 3 – Total permanent displacements from the Plaxis analyses

RSN	**Analysis Case 1** *X: Comp A (m)*	**Analysis Case 2** *X: Comp A, Y: Comp B (m)*	**Ratio** *Case 2 / Case 1*	**Analysis Case 3** *X: Comp B (m)*	**Analysis Case 4** *X: Comp B, Y: Comp A (m)*	**Ratio** *Case 4 / Case 3*
80	0.01	0.017	1.80	0.024	0.028	1.18
765	0.33	0.38	1.15	0.13	0.26	1.95
8165	0.14	0.23	1.72	0.23	0.28	1.22
5618	0.10	0.13	1.28	0.12	0.15	1.24

Table 4 - Total permanent displacements from the OpenSees analyses

RSN	**Analysis Case 1** *X: Comp A (m)*	**Analysis Case 2** *X: Comp A, Y: Comp B (m)*	**Ratio** *Case 2 / Case 1*	**Analysis Case 3** *X: Comp B (m)*	**Analysis Case 4** *X: Comp B, Y: Comp A (m)*	**Ratio** *Case 4 / Case 3*
80	0.04	0.10	2.47	0.07	0.07	1.05
765	0.09	0.20	2.17	0.16	0.17	1.08
8165	0.15	0.44	2.86	0.16	0.33	2.08
5618	0.12	0.21	1.75	0.10	0.23	2.18

Table 5 - Total permanent displacements from the FLAC analyses

RSN	**Analysis Case 1** *X: Comp A (m)*	**Analysis Case 2** *X: Comp A, Y: Comp B (m)*	**Ratio** *Case 2 / Case 1*	**Analysis Case 3** *X: Comp B (m)*	**Analysis Case 4** *X: Comp B, Y: Comp A (m)*	**Ratio** *Case 4 / Case 3*
80	0.01	0.025	2.50	0.035	0.06	1.71
765	0.46	0.67	1.46	0.17	0.34	2.00
8165	0.13	0.25	1.92	0.23	0.29	1.26

4. Comparison of Models

Figure 6 compares the estimated total absolute displacements calculated by each program for each ground motion and analysis case. For RSN 80, OpenSees predicts the largest displacements, however, for RSN 765 FLAC predicts the most displacements. None of the programs predicts consistently higher or lower values of displacement, which demonstrates that none of them have a bias. However, in some cases, the modelling uncertainty is greater than the difference between analyses with one or two components.

Figure 7 compares the ratio of when two components are applied compared to when only one component is applied. OpenSees predicts a higher ratio more often than the other programs and Plaxis predicts a lower ratio more often, however no program consistently predicts higher or lower ratios between when different number of components are used.

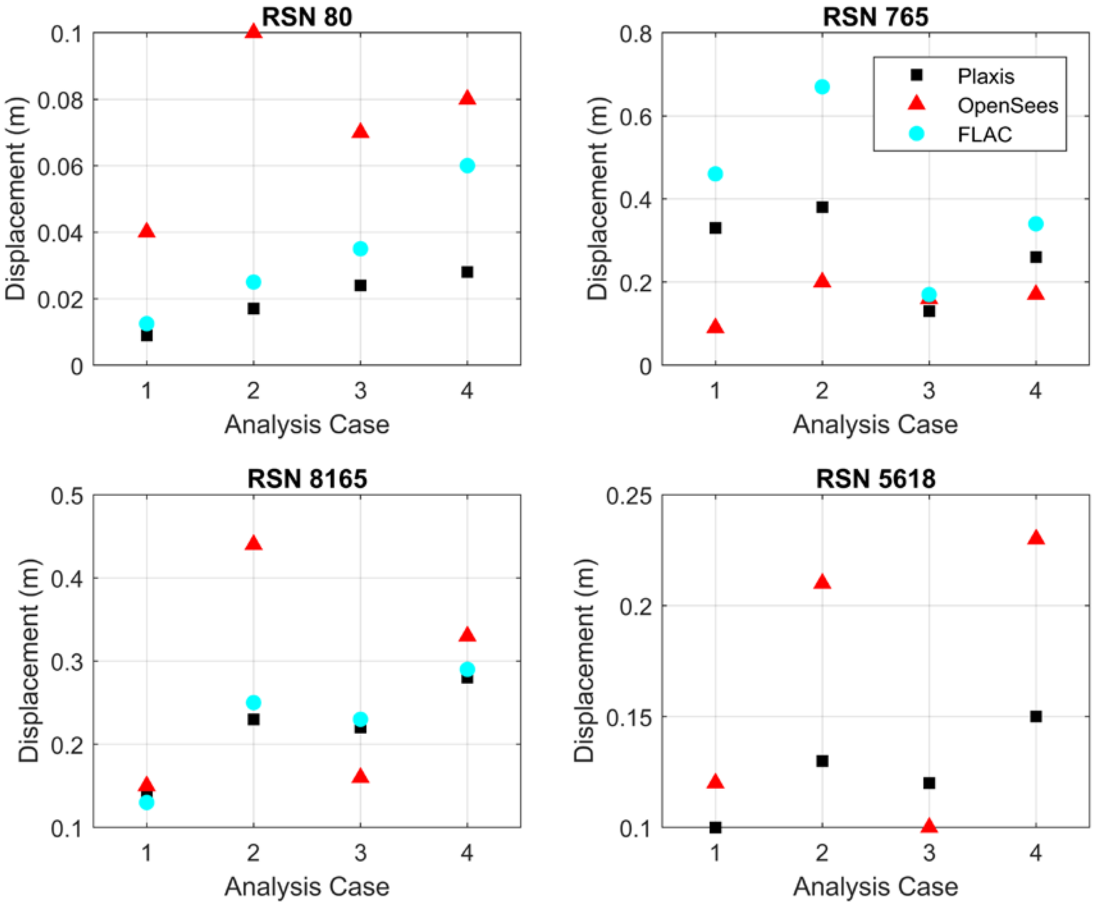

Fig. 6 – Comparison of total absolute displacements calculated by each program for each ground motion and analysis case.

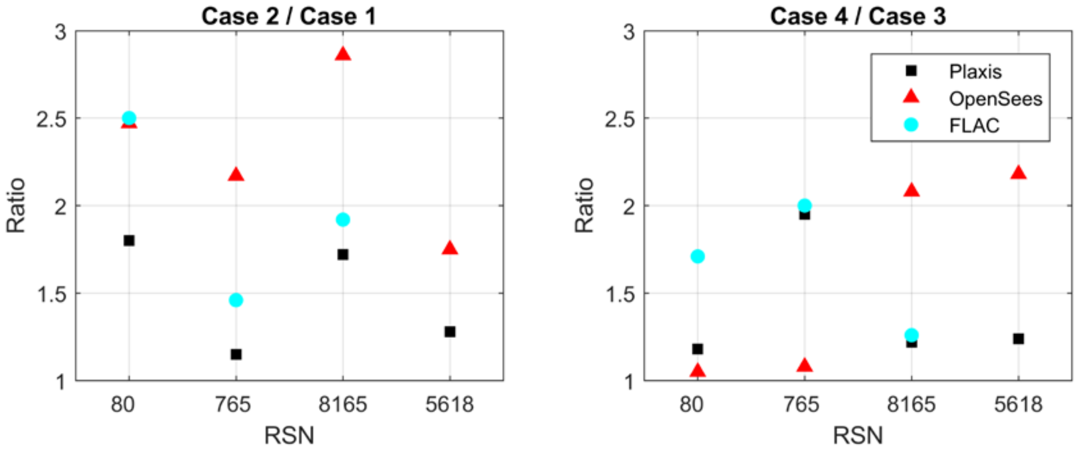

Fig. 7 – Comparison of the ratio between when two components are applied and only one component is applied for each program and ground motion.

We did not find any correlation between ground motion intensity or duration with which program predicted the most or least amount of displacement or ratio. However, the results are based on only four earthquakes. Ideally, more earthquakes should be tested to obtain a statistically significant comparison. This was not possible however, due to the long computation times for the Plaxis and FLAC models.

The differences in the results are due to the differences in geometry, numerical method, and boundary conditions. The model in OpenSees is a soil column with altered gravity to approximate an infinite slope, whereas the other two are large finite slope models. Plaxis and OpenSees are finite element programs whereas FLAC is a finite difference program. OpenSees and FLAC have free field lateral boundaries whereas the Plaxis model uses viscous boundaries. Therefore, differences between the results of the three programs demonstrate the uncertainty in modelling, which is often neglected in most slope stability analyses.

5. Summary and conclusions

This study compares the results of multidirectional shaking on slopes calculated using the finite element programs OpenSees and Plaxis, and the finite difference program FLAC. We use one slope profile with slope angle of 15 degrees and four two-component ground motions from active crustal regions. We performed three-dimensional seismic slope stability analyses in all three programs for four different cases 1) component A in the x direction; 2) component A in the x direction and component B in the y direction; 3) component B in the x direction; 4) component B in the x direction and component A in the y direction. The main objectives of this benchmarking study are to validate the results of Carlton and Kaynia (2016) [6] in other numerical programs, to investigate the effect of modelling uncertainty on slope displacement due to multidirectional shaking, and to evaluate which program(s) to use in a future parametric study.

The results show that regardless of ground motion or numerical program, when two ground motion components are applied, one in the downslope and one in the cross-slope direction, the predicted displacements are larger compared to when only one component is applied in the downslope direction. This validates the results of Carlton and Kaynia (2016) [6], and shows that an increase in displacements is not program, slope or ground motion specific. However, there is a large difference in displacements depending on which component is applied in the downslope direction and which in the cross-slope direction. Therefore, careful consideration should be taken when applying ground motions for dynamic slope stability analyses.

In addition, there is also scatter between the results of the three programs, both the absolute displacements and the ratios of analyses with two components compared to one component. In some cases, the modelling uncertainty is greater than the difference between analyses with one or two components. However, the general trends are similar between all three programs and none of the programs shows a consistent high or low bias in its results.

For future research, we will conduct analyses in OpenSees as it is able to perform the calculations much faster and produces similar results to Plaxis and FLAC. The next steps include varying the slope's geometry and material, using an advanced constitutive model, and applying more earthquake motions to identify a relationship between the displacements calculated when using one versus two components of earthquake motion.

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