# Behaviour of slopes under multiple adjacent footings and buildings

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**Abstract.** This article studies response of soil slopes under adjacent embedded strip foundations, subjected to increasing vertical load due to gravity load of buildings. The study also considers slopes under closely spaced adjacent buildings. In addition, the article addresses the effect of horizontal earthquake loading by the simplified pseudo-static method. Response of two representative slopes is investigated using nonlinear 2D Finite Element Limit Equilibrium Analysis with strength reduction method. The effect of interaction between building, foundation, and slope on the sliding surface, factor of safety (FOS), and ultimate load intensity (ULI) is explored. Furthermore, the effect of integral action of building frame on slope-building interaction is investigated. It is found that the buildings/foundations mostly result in local failure of stable slopes under gravity and seismic loads. Consequently, the slope's FOS is found to be sensitive to foundation loading intensity, but in most of the considered cases it is insensitive to the number and distance between adjacent foundations and buildings.

**Keywords:** Slope stability; Strength reduction method; Slope-building interaction; Foundation on slope; Seismic coefficient; Hill-side building

## 1. Introduction

Rapid urbanization and scarcity of flat land in hilly areas are forcing people to involve in heavy constructions on hill slopes. In many cases, hilly areas of cities with attractive views represent luxurious conditions for housing development. Despite unfavorable conditions, densely located low- to medium-rise buildings are being constructed, resulting in increasing loads on slopes. The foundations of these buildings are often constructed at different levels in the influence zone of each other, due to limited space and restricted bay lengths. Some of the hilly areas are not only densely populated (e.g. Himalayas as shown in Fig. 1), but are also prone to seismic activities. In some countries, the construction regulatory agencies are struggling with the questions regarding the effect of height and density of buildings on hill slopes, and formulation of relevant guidelines. Various existing standards/codes primarily focus on the design of buildings in flat regions, with only limited guidance for the design of buildings on hill slopes. The available literature on slope stability mostly deals with slopes under distributed loading, which is an over-simplified approach for considering slope-building interaction (SBI).

(a) (b)

**Fig. 1.** Closely located buildings on hill slopes, in two typical cities in Indian Himalayas: a) Mussoorie; and b) Nainital

The past studies (Das and Larbi-Cherif 1983; Kumar and Ghosh 2007; Kumar and

Kouzer 2008; Lee and Eun 2009; Mabrouki et al. 2010; Kumar and Bhattacharya 2010) show that the ultimate load intensity (ULI) supported by a foundation on flat ground, is enhanced in presence of closely spaced adjacent foundations. However, to the knowledge of the authors, no such study is available for the closely spaced adjacent foundations on hill slopes, and only few studies have been reported on the effect of building load on slope stability. Paul and Kumar (1997) studied the stability of slopes subjected to building and seismic loads, and concluded that the slope may fail in two ways: first, local failure near the building foundation, and, second, global failure of slope including the building-foundation system. Kourkoulis et al. (2010) in their study on foundations located above the slope, observed that the position of the sliding surface, failure mechanism, and total and differential displacements are significantly affected by the type of shallow foundation (isolated and rigid raft), foundation distance from the crest of the slope and surcharge load on the foundation. No such study is available for foundations located on the face of the slope. Further, the interaction between adjacent buildings located on slopes, having foundations located in the influence zone of each other, has not been studied either.

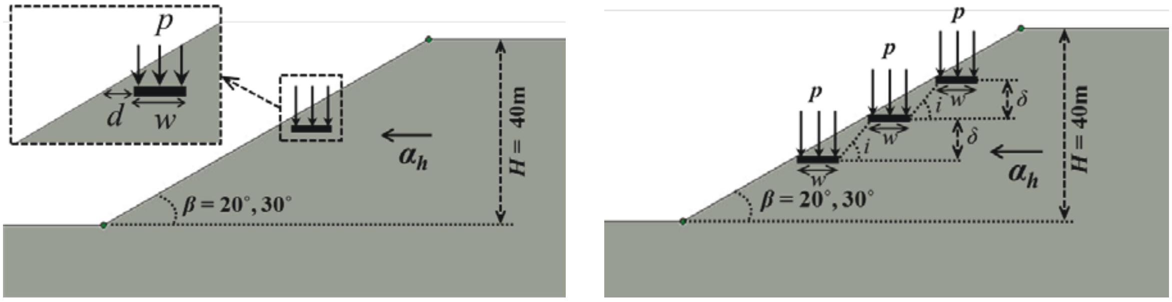
A deeper insight is required into the behavior of slopes under building and seismic loads. This is a complex problem that requires detailed numerical study involving realistic modeling of slopes and buildings. In this article, a study is presented on the stability of slopes considering closely-spaced adjacent footings/buildings placed on the face of slopes and subjected to seismic loads. To investigate the stability of slopes of varying geometry and soil properties, integrated 2D nonlinear Finite Element (FE) models of slope and foundations/buildings have been developed. The hill slopes are known to have a complex variation of material properties across the cross-section; however, the present study focuses on understanding of the slope-building interaction (SBI) under seismic action, and is therefore limited to slopes of homogeneous soil properties. Most of the conclusions, however, are equally valid for in-homogeneous slopes with variable soil properties.

## 2. Numerical Study

In the present study, two homogeneous slopes having the same height, $H$ = 40 m, from the slope toe and with slope angles, $\beta$ = 20° and 30°, have been considered with material properties similar to those used by Fotopoulou and Pitilakis (2013) (see Table 1). The stability of the slopes has been studied under gravity and seismic actions along with individual strip foundations and their combinations as well as considering the integral action of building frames. Variation in slope's FOS with foundation load intensity and seismic load (considered as pseudo-static force in terms of horizontal seismic coefficient, $\alpha_h$) has been investigated. Strip foundations of widths, $w$ = 1.5 m, 3.0 m and 6.0 m have been considered at three different offset distances (i.e. distance of foundation from the face of the slope), $d$ = 0 m, 1.5 m and 3 m, as shown in Fig. 2(a). For a fair comparison, the multiple adjacent foundations have been considered at zero offset distances in all the cases.

**Table 1.** Soil parameters

| Properties | 20° Slope | 30° Slope |
|---|---|---|
| Soil Type | Stiff soil (Clay) | Stiff soil (Sand) |
| Unit Weight, $\gamma$ (kN/m$^3$) | 20 | 20 |
| Poisson's Ratio, $v$ | 0.3 | 0.3 |
| Cohesion, $c$ (kPa) | 50 | 10 |
| Angle of internal friction, $\phi$ | 27° | 44° |
| Shear wave velocity, $Vs$ (m/s) | 500 | 500 |
| Young's modulus, $E$ (MPa) | 1300 | 1300 |




(a) (b)

**Fig. 2.** Schematic diagram showing typical foundation locations on a slope: (a) single foundation; and (b) adjacent multiple foundations

Codes often consider the influence of loads through a load-spreading angle. In this line, the Indian code IS1904 (1986) considers the influence of adjacent foundations on slopes in terms of influence angle, *i* (angle of the line joining adjacent ends of foundations from the horizontal, as shown in Fig. 2(b)) and recommends a maximum value of 30º. To study the effect of influence angle on slope stability in the present study, the adjacent foundations on slopes have been arranged to have the influence angles, *i* either less than 30° or greater than 30°. However, for the 30° slope, and for wider foundation (*w* = 6m) even in case of the 20° slope, the influence angle less than 30° is not possible. In these cases, only the combinations with *i* greater than 30° have been studied.

To study the effect of integral frame action of buildings on redistribution of foundation loads and hence on the stability of the slopes, two and four storey buildings having irregular 'step-back' configuration to suit the slope geometry, have been placed on the slope (number of storeys is counted above the top-most foundation level). Figure 3 shows the plan and elevations of the buildings considered in the present study. In the 2D model, one single frame (Frame 'B') has been modeled with tributary loads on beams and columns (as shown in the Fig. 3). All the buildings have been supported by strip foundations embedded to an average depth of 1.5 m below the soil surface. The sizes of the foundations have been obtained for the vertical loads alone using available literature (Kumar and Ghosh 2006) for the design of individual strip foundation on slopes. As stated earlier, one of the objectives of the present study is to investigate the effect of variation of load intensity on slope stability. To achieve the varying load intensity on foundations, the foundation sizes have been estimated for the 4-storey buildings and the same sizes of foundations have been used for the 2-storey buildings, resulting in reduced load intensity on foundations. The material properties of the structural elements (beams, columns and foundations) have been considered as, unit weight, $\gamma$ = 25 kN/m$^3$; Poisson's ratio, $\nu$ = 0.20 and Young's modulus, $E$ = 27 GPa. The storey height and bay length of the buildings are 3.3 m and 5.0 m, respectively, and the beam sizes are 0.23 m × 0.40 m while the column sizes are 0.40 m × 0.40 m and 0.60 m × 0.60 m, as shown in Table 2. These dimensions represent realistic values following design codes for reinforced concrete frame buildings.

**Table 2.** Member Sizes and Load Distribution

| Member* | | Storey/Floor no.* | | Dimensions | | Load (kN[§], kN/m[#]) |
|---|---|---|---|---|---|---|
| | | 20° Slope | 30° Slope | B (mm) | D (mm) | |
| Beams | All | F0, F1, F2, F3, F-1 | F0, F1, F2, F3, F-1, F-2 | 230 | 400 | 13.13[§] |
| | | R | R | 230 | 400 | 23.55[§] |
| Columns | B2, B3 | F1, F2, F3 | F1, F2, F3 | 400 | 400 | 176.10[#] |
| | | R | R | 400 | 400 | 124.00[#] |
| | B1, B4 | F1, F2, F3 | F1, F2, F3 | 400 | 400 | 143.80[#] |
| | | R | R | 400 | 400 | 67.75[#] |
| | B1, B2 | F0 | F-1 | 400 | 400 | 143.80[#] |
| | B1, B3 | -- | F0 | 400 | 400 | 143.80[#] |
| | B2 | -- | F0 | 400 | 400 | 176.10[#] |
| | B4 | F0 | F0 | 600 | 600 | 143.80[#] |

**Refer to Figure 2 for numbering of beams, columns and storey/floor; [§]Uniformly distributed load (kN/m) on beams; [#]Concentrated / Point load (kN) on columns*

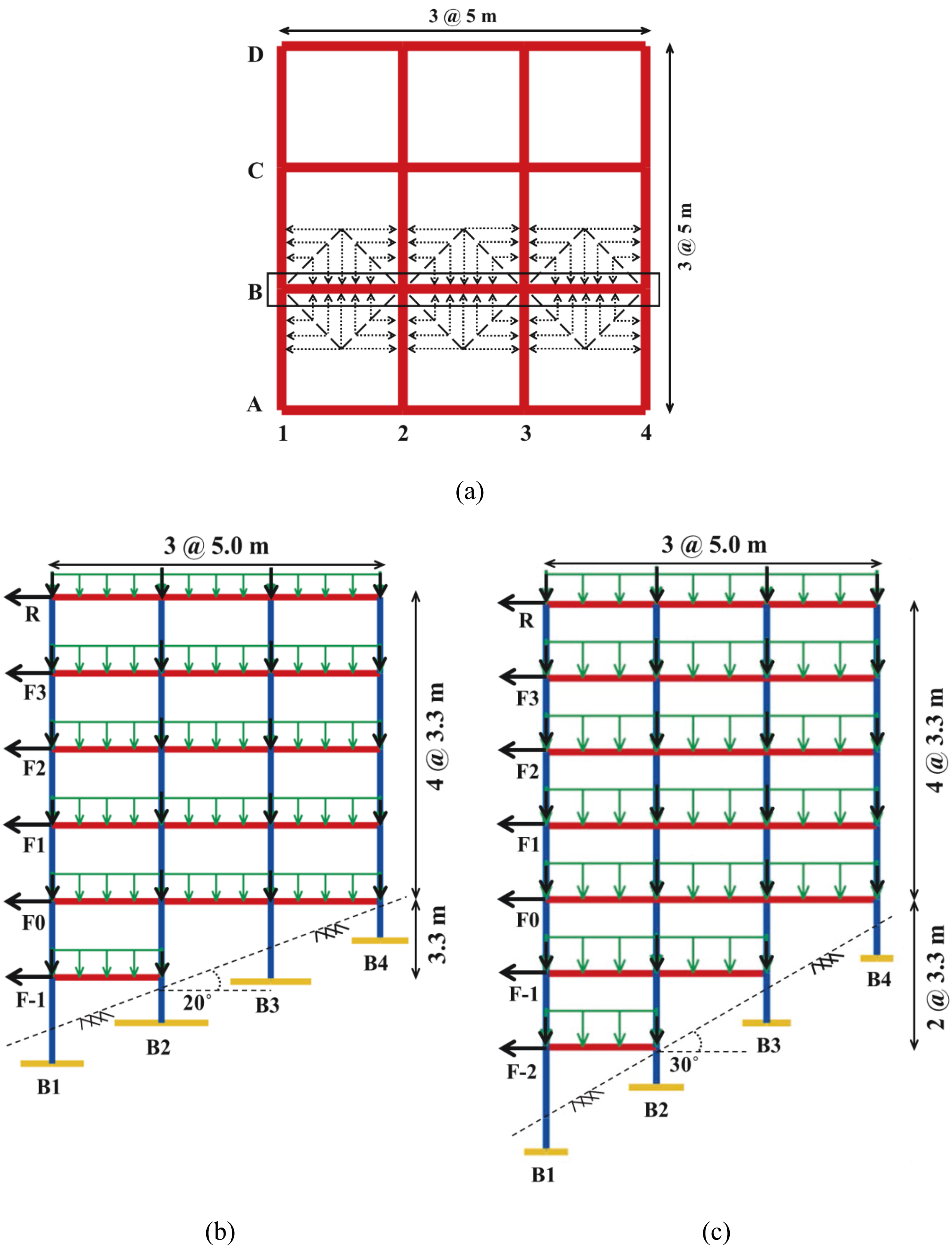



**Fig. 3.** Plan and elevations of the considered buildings: (a) plan showing tributary load on a typical frame 'B'; (b) elevation on 20º slope; and (c) elevation on 30º slope

## 3. Modelling and Analysis

In the present study, Finite Element Limit Analysis (FELA) based on strength reduction method (SRM) has been performed to evaluate the FOS of slopes under buildings/foundations using OptumG2 (2017) software. In this approach, the SRM analysis proceeds by computing a strength reduction factor by which the material parameters are reduced in order to attain a state of incipient failure ( Matsui and San 1992; Dawson et al. 1999; Griffiths and Lane 1999; Zheng et al. 2005). An elasto-plastic constitutive model based on Mohr-Coulomb failure criterion and following associated flow rule has been used for soil modeling in FELA. At the base of the FE model of the slope, the movements in both directions are restrained (i.e. both X- and Y-displacements are zero), while for the left and right lateral boundaries, only vertical displacement is allowed (i.e. X-displacement is zero). The lateral extent of model has been considered using a sensitivity study so that the effect of boundary conditions on the domain of interest is insignificant. A detailed study on validation of the slope-foundation model has been presented in Raj and Singh (2016).

To study the effect of meshing and element type and size, finite element models of the two free slopes ($H$ = 40 m, $\beta$ = 20º and 30º with properties as shown in Table 1) were developed using conventional and adaptive meshing options with Lower Bound (LB), Upper Bound (UB), 6-node Gauss, and 15-node Gauss, triangular plane strain elements available in OptumG2. These results are also compared with the Strength Reduction Finite Element Method (SRFEM) using ABAQUS (2016) and the Bishop's simplified method using Slope/W (2012) software. All the analyses yielded close estimates of FOS as also observed by Tschuchnigg et al. (2015). The analysis using adaptive meshing with 15-node elements has the fastest convergence; it yields precise location of failure slip surface, and requires a smaller number of elements to achieve the same level of accuracy, as also observed by (Loukidis and Salgado 2009). In view of these observations (numerical results not presented here for brevity), the adaptive meshing technique with 15-node triangular elements has been used for further analyses in the present study.

All beams, columns and foundations of the considered building frames have been modelled using elastıc 'plate' element available in OptumG2 element library. The two node elastic plate element in plane strain domain actually acts like standard Euler-Bernoulli beam element. The foundations have been embedded in soil and interface elements have been used on both sides of the embedded foundations to transfer shear and normal stresses from the foundation to the soil. In OptumG2, the interface properties can be simulated by applying a reduction factor, $R$ to the interface material properties. A numerical study with varying $R$ indicates only minor sensitivity of the FOS to this parameter (results not shown here for brevity), and $R = 1$ has been considered in the present study. The live load and loads from other building components such as slabs and infills (partitions) have been applied as equivalent uniformly distributed loads on beams and concentrated loads at columns (Fig. 2) at each floor for the analyses of coupled building-slope systems.

To simulate the seismic effect on the coupled slope-foundation-building system, pseudo-static forces have been applied on the entire soil mass, in terms of horizontal seismic coefficient, $\alpha_h$. Design codes treat this coefficient differently. In Eurocode, as well as in the Indian practice, this coefficient is taken as 50% of the peak ground acceleration used for the earthquake analyses of the structure. In Indian code the design EPGA for buildings is considered as half of the zone factor, $Z$, which represents the Effective Peak Ground Acceleration (EPGA) at Maximum Considered Earthquake (MCE) hazard level. Accordingly, the horizontal seismic coefficient, $\alpha_h$ has been considered as one fourth of the corresponding zone factor.

The lateral force acting on the building has been estimated for the same values of $Z$, using a dynamic mode superposition method. This method, recommended by most current seismic design codes, considers the effect of inelastic energy dissipation on the actual force transmitted to foundation-soil, indirectly using a response reduction factor (or behaviour factor). To find out the lateral forces acting on the buildings due to earthquake, first the buildings have been modelled with fixed base condition in SAP2000 structural analysis and design software, and mode superposition analysis has been performed. It is interesting to note that for short period ($T \leq 0.4$ s) buildings also, the base shear coefficient, $A_h$ also works out to be equal to Z/4, using a response reduction factor of 5, as recommended by IS 1893(Part 1) : 2016.

However, it is to be noted that the structures yield at a much higher base shear than that used in design, due to overstrength arising from various factors, such as difference between the expected (mean) and specified strength of materials, partial factors of safety used in the limit state design, etc. The value of this overstrength factor for RC frame buildings designed for Indian codes, has been estimated as 2.0 (Khose et al. (2012); Haldar and Singh (2009). The intention of this study is not to make a specific design, rather give insight into the role of earthquake loads on the behaviour of the building-slope interaction. Considering the overstrength, the effective value of lateral seismic coefficient, $\alpha_h$ has been considered as 0.12 g for Zone IV, and 0.18 g for Zone V. The estimated base shear is distributed along the height of the building in a combination of different mode shapes, and the storey forces thus obtained (as shown in Table 3) are applied on the corresponding soil-building coupled models in OptumG2.

**Table 3.** Lateral forces at different floor levels obtained from mode superposition analysis of fixed-base buildings

| Storey/ Floor No. | Lateral load (kN) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Buildings on 20° Slope | | | | Buildings on 30° Slope | | | |
| | 2-storey | | 4-storey | | 2-storey | | 4-storey | |
| | $\alpha_h =$ 0.12g | $\alpha_h =$ 0.18g | $\alpha_h =$ 0.12g | $\alpha_h =$ 0.18g | $\alpha_h =$ 0.12g | $\alpha_h =$ 0.18g | $\alpha_h =$ 0.12g | $\alpha_h =$ 0.18g |
| R | -- | -- | 104 | 155 | -- | -- | 115 | 174 |
| F3 | -- | -- | 66 | 100 | -- | -- | 55 | 81 |
| F2 | 82 | 123 | 38 | 57 | 88 | 132 | 39 | 59 |
| F1 | 64 | 115 | 46 | 68 | 57 | 85 | 41 | 82 |
| F0 | 64 | 76 | 101 | 152 | 64 | 96 | 81 | 101 |
| F-1 | 24 | 36 | 44 | 51 | 39 | 59 | 56 | 84 |
| F-2 | -- | -- | -- | -- | 24 | 36 | 38 | 58 |

## 4. Results and Discussion

### 4.1 Slopes under single strip foundation

Figures 4 (a-c) show the typical failure surfaces of the 20° slope under gravity action alone, whereas Figs. 4 (d-f) show the corresponding failure surfaces under combined gravity and seismic actions. In the latter case, the soil mass and foundation (including the vertical load acting on the foundation) both are subjected to the corresponding value of $\alpha_h$, in the down-slope direction. The failure surface indicated by displacement vectors, is shown for the considered slope without building load (free slope) and for the case loaded with a strip foundation ($w$ = 6.0 m, and $d$ = 0 m). Two levels of vertical load intensity on the foundations are considered. Figures 4(b and e) represent a mild loading (150 kN/m$^2$) on the foundation, whereas Figs. 4(c and f) represent heavy loading (1100 kN/m$^2$ and 700 kN/m$^2$, respectively) close to the ultimate load intensity. Similar results have also been obtained for the 30° slope, but not shown here for brevity. These results show that the failure modes in case of slopes with heavily loaded foundations are quite different from those of the corresponding free slopes and slopes with mildly loaded foundations. The slopes under heavily loaded foundations failed in local mode (i.e. failure of soil in the vicinity of the foundation), irrespective of the foundation size, offset distance and location (not shown in the figure), whereas the free slopes failed in a global mechanism. As evident from Figs. 4(c and f), in case of slope failure under foundation load, the foundation and soil above the foundation also undergo a translational and rotational movement due to asymmetric failure.

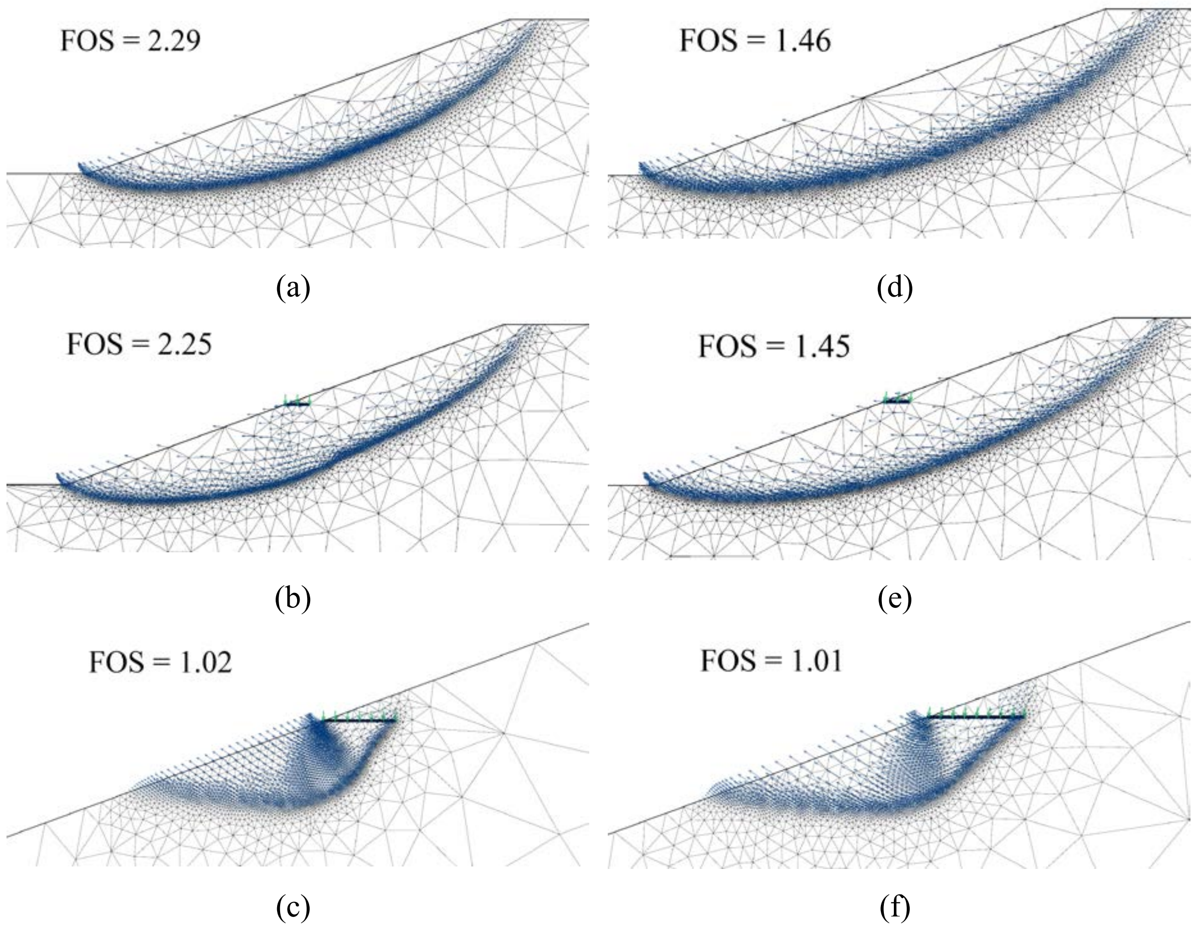



**Fig. 4.** Displacement vectors showing failure surfaces for 20º slope: (a) free slope, $\alpha_h$ = 0 g; (b) slope loaded with a mild intensity of vertical load on a single strip foundation, $\alpha_h$ = 0 g; (c) slope loaded with high intensity of vertical load on a single strip foundation, $\alpha_h$ = 0 g; (d) free slope, $\alpha_h$ = 0.18 g; (e) slope loaded with a mild intensity of vertical load on a single strip foundation, $\alpha_h$ = 0.18 g; (f) slope loaded with high intensity of vertical load on a single strip foundation, $\alpha_h$ = 0.18 g.

Variation of FOS of the 20º and 30º slopes under increasing gravity and seismic load intensities on a single strip foundation is shown in Figs. 5 and 6, respectively. The left column of the figures (a-c) presents the variation of FOS with offset distance, whereas, the right column (d-f) presents the variation of FOS with foundation width. It can be observed from the figures that the variation of FOS with load intensity is relatively flat initially, followed by a steep decline in FOS with increasing foundation load intensity. It has been observed that at a threshold foundation load intensity (corresponding to the sharp change in the shape of FOS- load Intensity curve), the critical failure surface of the slope changes from global to local. This indicates that at smaller (than threshold) load intensity, the failure mode is global (see Figs. 4(b and e)), whereas in case of higher load intensities, the failure mode is local (see Figs. 4(c and f)). As expected, the offset distance and width of the foundation both have significant effect on the FOS. The effect of seismic intensity, $\alpha_h$ is quite significant on the FOS of free slopes and slopes with mild intensity of vertical load, but it diminishes to some extent with increasing load instensity. Another interesting observation from Figs. 5 and 6 is regarding the ultimate load intensity (ULI) of foundations, i.e. the foundation load intensity corresponding to the FOS=1.0. In most of the considered cases, for a particular value of $\alpha_h$, the ULI increases with width as well as with offset distance of the foundation, for both 20º and 30º slopes. Further, in all the considered cases, for a given offset distance and width of foundation, the ULI decreases, with increasing $\alpha_h$.

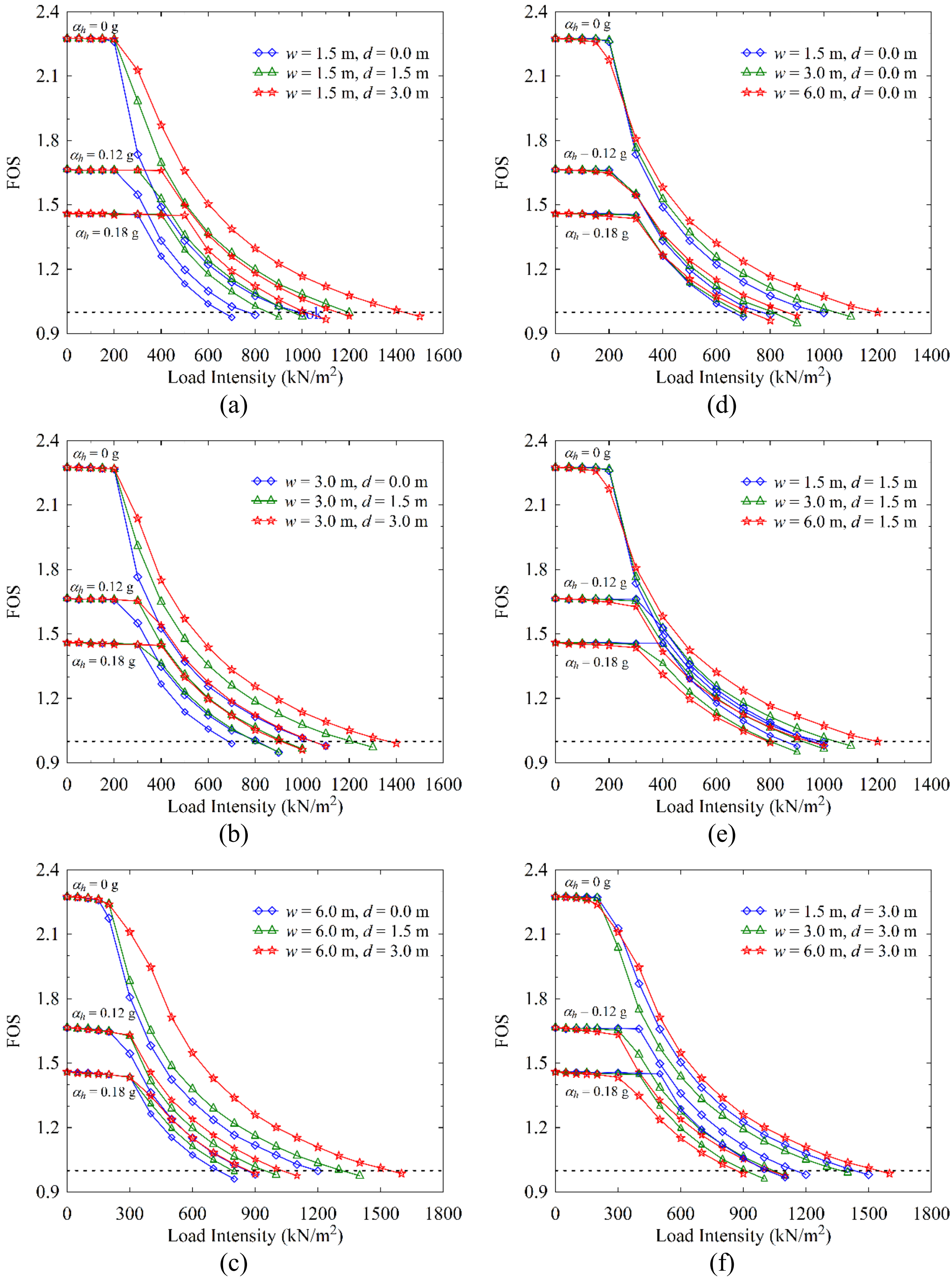



**Fig. 5.** Variation of FOS of the 20º slope under gravity and seismic actions, subjected to increasing foundation load intensity on a single strip foundation having different widths and offset distances: (a-c) effect of increasing offset distance for a foundation of a given width; and (d-f) effect of increasing width for a foundation at a given offset distance.

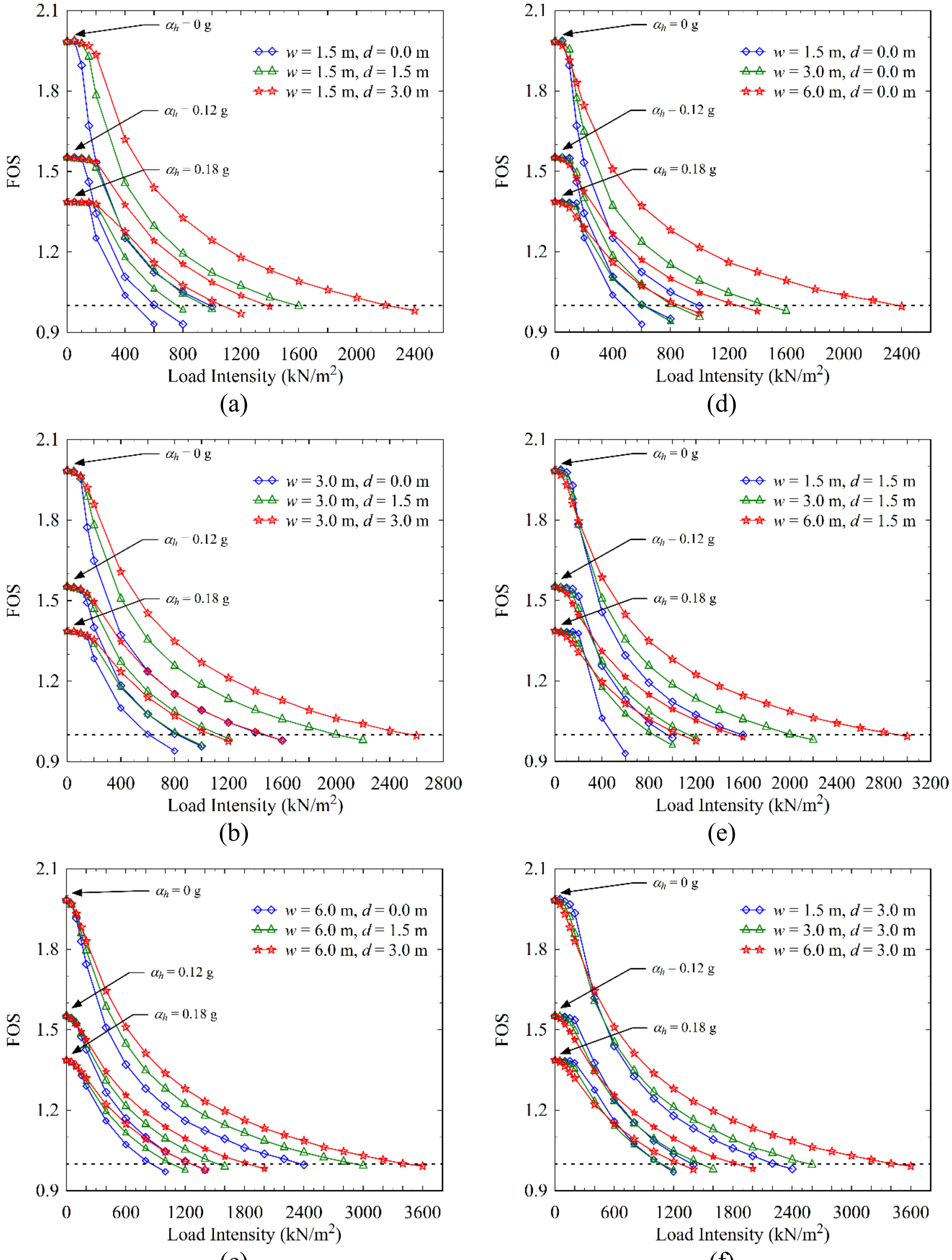



**Fig. 6.** Variation of FOS of the 30º slope under gravity and seismic actions, subjected to increasing foundation load intensity on a single strip foundation having different widths and offset distances: (a-c) effect of increasing offset distance for a foundation of a given width; and (d-f) effect of increasing width for a foundation at a given offset distance.

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### 4.2 Slopes under multiple strip foundations

Adjacent foundations, depending on the distances between them, may interact and influence the failure mechanism and hence the FOS of the slope. Further, in case of foundations on slopes, the total vertical load acting on the slope is proportional to the number of foundations for a given loading intensity and size of foundations. The seismic action, considered to be acting in downslope direction, is expected to increase the slope instability. To study the effect of adjacent foundations on slopes under gravity and seismic events, two and three foundations have been placed adjacent to each other, with varying distances between them. The distances between the foundations have been selected in such a way that the influence angle, $i$ (Fig. 2(b)) varies within the desired range and represents a practically feasible placement of foundations. For a consistent comparison, all the foundations have been kept adjacent to the slope surface.

Response of the slopes has been obtained in terms of FOS, and compared (Fig. 7) with the corresponding response under single foundation. It is evident from the figure that, in all the cases considered in this study, the effect of adjacent foundations on slope stability is relatively insignificant in comparison with the effect of other parameters. Further, the variation of FOS with the loading intensity follows the same trend as in case of single foundation; that is, there is negligible influence of loading intensity in the initial range followed by a rapid drop beyond a threshold loading intensity. Ultimate load intensity corresponding to slope failure (i.e. FOS $\approx$1) in different cases, has been estimated (values not shown here for brevity) and it has been observed that only slight (2-19 %) decrease occurs in the ultimate load intensity for two and three adjacent foundations, as compared to a single foundation. This has been observed even when the adjacent foundations are placed with $i < 30^{\circ}$ and subjected to the combined effect of gravity and seismic loading.

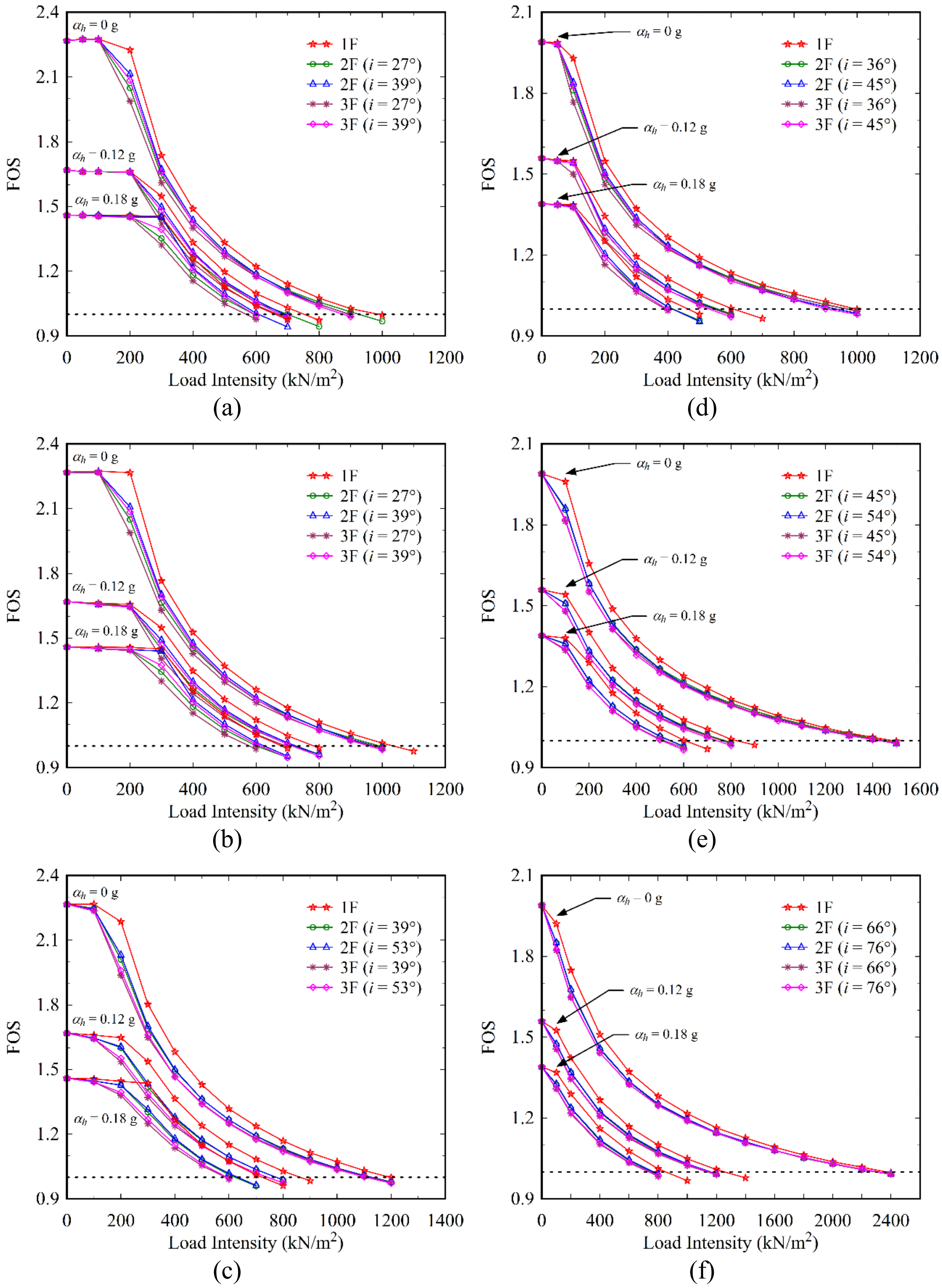



**Fig. 7.** Variation of FOS with increasing foundation load intensity on a single and multiple adjacent strip foundations located on: (a) 20º slope, $w$ = 1.5 m; (b) 20º slope, $w$ = 3.0 m; (c) 20º slope, $w$ = 6.0 m; (d) 30º slope, $w$ = 1.5 m; (e) 30º slope, $w$ = 3.0 m; and (f) 30º slope, $w$ = 6.0 m.

The insensitivity of the slope FOS to the number of adjacent foundations can be understood from the failure mechanism of the slopes under multiple foundations. It is interesting to note that the failure occurs in local mode (Fig. 8) even under multiple foundations subjected to gravity and seismic loading. It is similar to the failure of the soil below the foundations on a flat ground, except that the foundations on slope result in asymmetric failure in down-slope direction. As mentioned earlier, in case of foundations on flat ground, the ultimate bearing capacity is enhanced due to closely spaced adjacent footings. However, in case of foundations on slopes, the enhanced overburden effect of the adjacent foundations cannot be mobilized due to asymmetric failure and the adjacent foundations result in insignificant influence on the ultimate load capacity of the foundation, even under gravity loading.

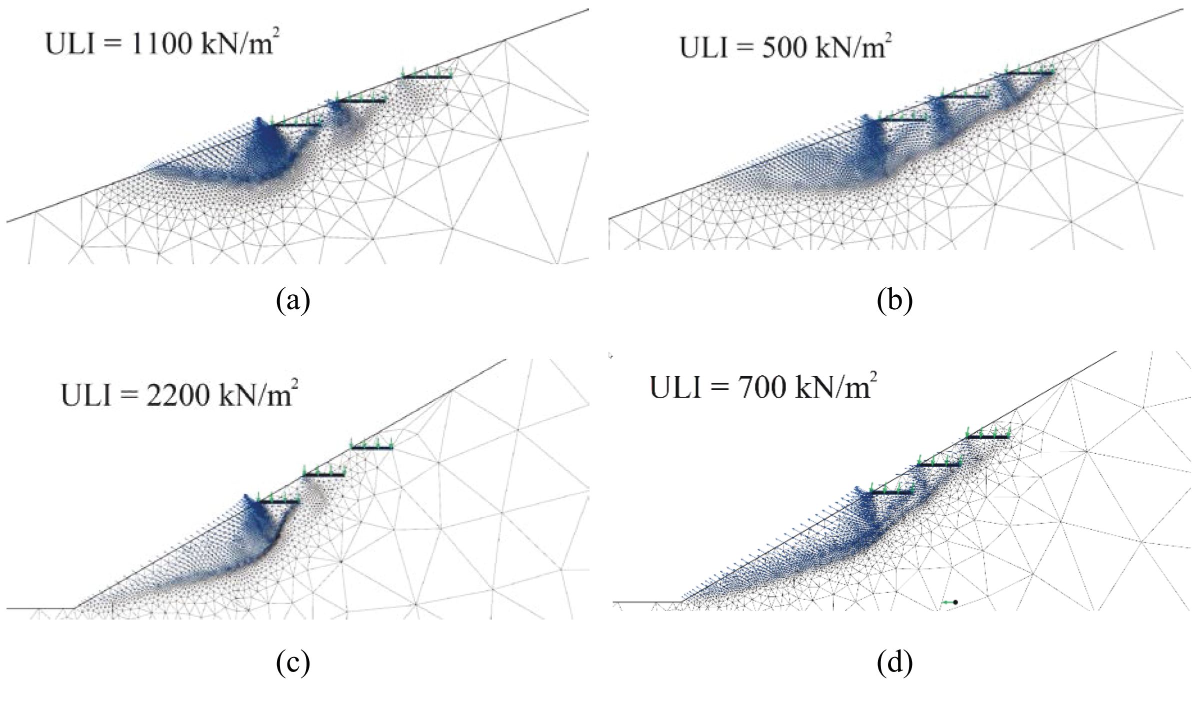



**Fig. 8.** Displacement vectors showing failure surfaces of slopes under three adjacent footings ($w$ = 6.0 m) : (a) 20º slope, $\alpha_h$ = 0 g; (b) 20º slope, $\alpha_h$ = 0.18 g; (c) 30º slope, $\alpha_h$ = 0 g; and (d) 30º slope, $\alpha_h$ = 0.18 g.

### 4.3 Stability of slopes under single building

In this part of the study, the effect of integral action of building frame-foundation system, is explored under gravity and seismic loading. Irregular (step-back) configuration RC frame buildings with varying height (2 and 4-storey) have been considered on the 20º and 30º slopes. The FOS and failure mechanisms of the considered slopes have been obtained by modelling the building and foundations together and compared with the case where only the foundations subjected to the corresponding horizontal and vertical loads and moments form the same buildings in fixed base condition under gravity and seismic loading, have been considered. Typical displacement vectors for the considered slopes under gravity loading, with and without integral action of a 2-storey building-foundation system are shown in Fig. 9. In the first case, all the foundations move together as an integral system (Figs. 9(a and c)), whereas in the second case, the displacement is accumulated at the level of the bottom-most foundation (Figs. 9(b and d)). This also results in a marginal increase in the FOS in case of integral model. Same trend has also been observed with the 4-storey building, where the FOS of slope increased from 1.50 to 1.57, in case of 20º and from 1.19 to 1.27 in case of 30º slope, when the integral action of frame-foundation system is considered.

Under combined action of gravity and seismic loading, the effect of integral frame action (Fig. 10) is very significant. Further, under combined action of gravity and seismic load, the largest displacement is observed at the level of the top-most foundation (Figs. 10(b and d)), when modelled without integral frame action. This can be attributed to the high shear force attracted by the short column supported on the top-most foundation in the irregular step-back structural configuration (Fig. 11(a and c)). The FOS, governed by the failure of the top-most foundation, shows significant decrease in this case. When modelled with the integral frame action, the column shear gets re-distributed among different foundations (Fig. 11(b and d)), resulting in more uniform distribution of lateral displacement, and significant increase in FOS of the building-slope system. In this case ($\alpha_h$ = 0.18 g), the FOS increases due to integral frame action, from 0.87 to 1.25 for the 4-storey building on the 20º slope and from 0.33 to 1.04 for the 4-storey building on the 30º slope.

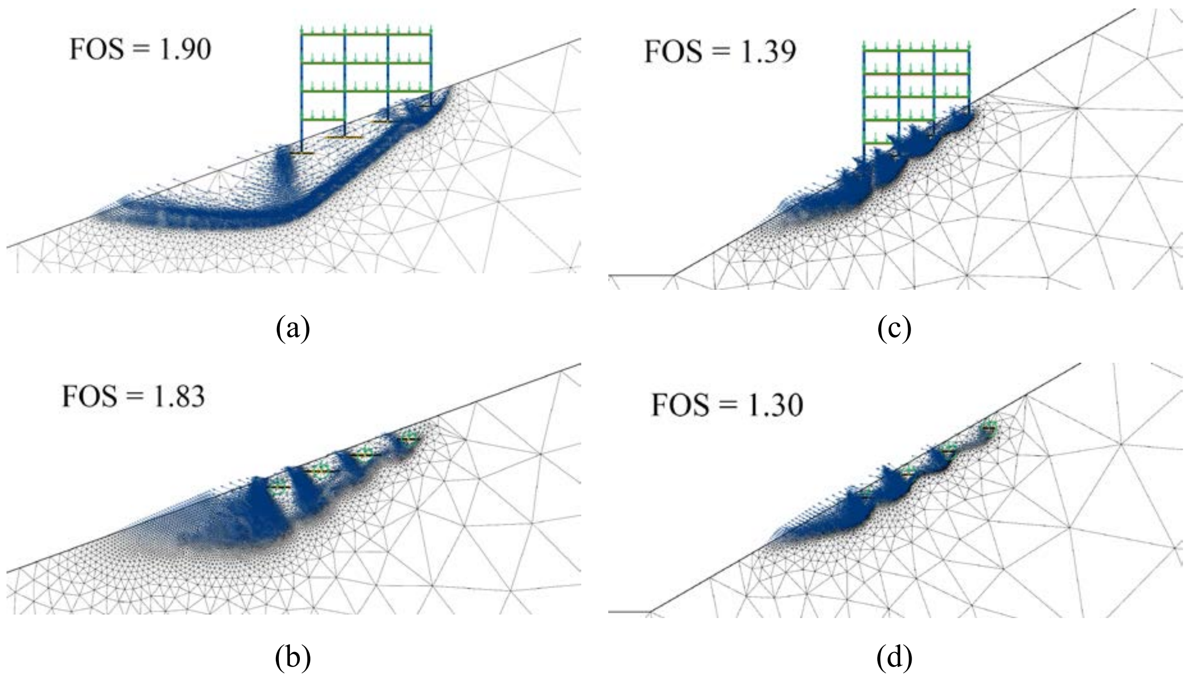
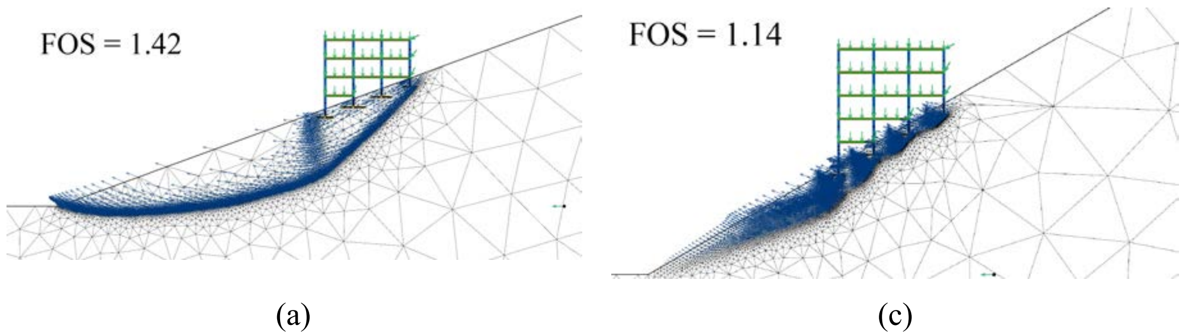
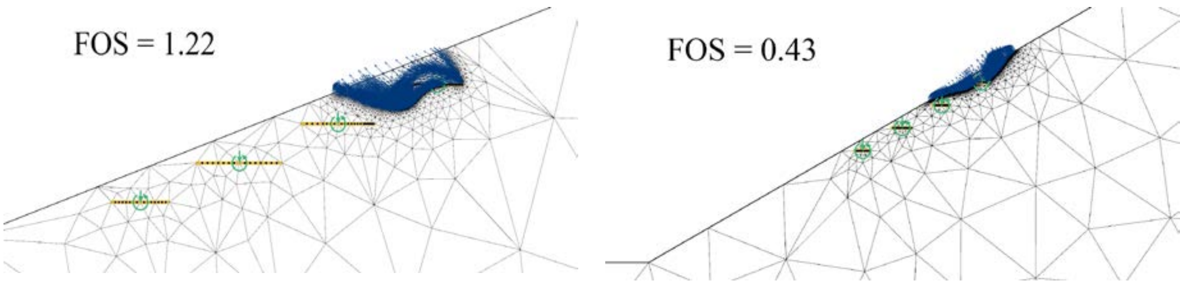


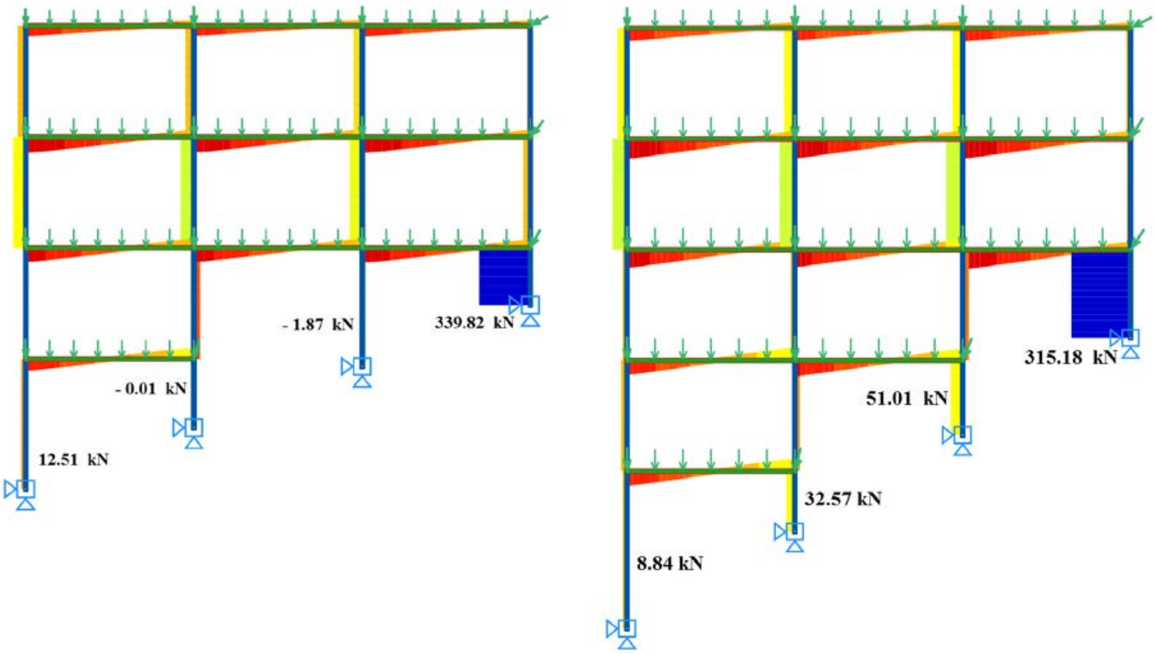

**Fig. 9.** Displacement vectors showing failure surfaces of slopes under gravity loading of 2-storey building: (a) 20º slope under integral building-foundation system; (b) 20º slope under independent foundations subjected to building loads; (c) 30º slope under integral building-foundation system; (d) 30º slope under independent foundations subjected to building loads.



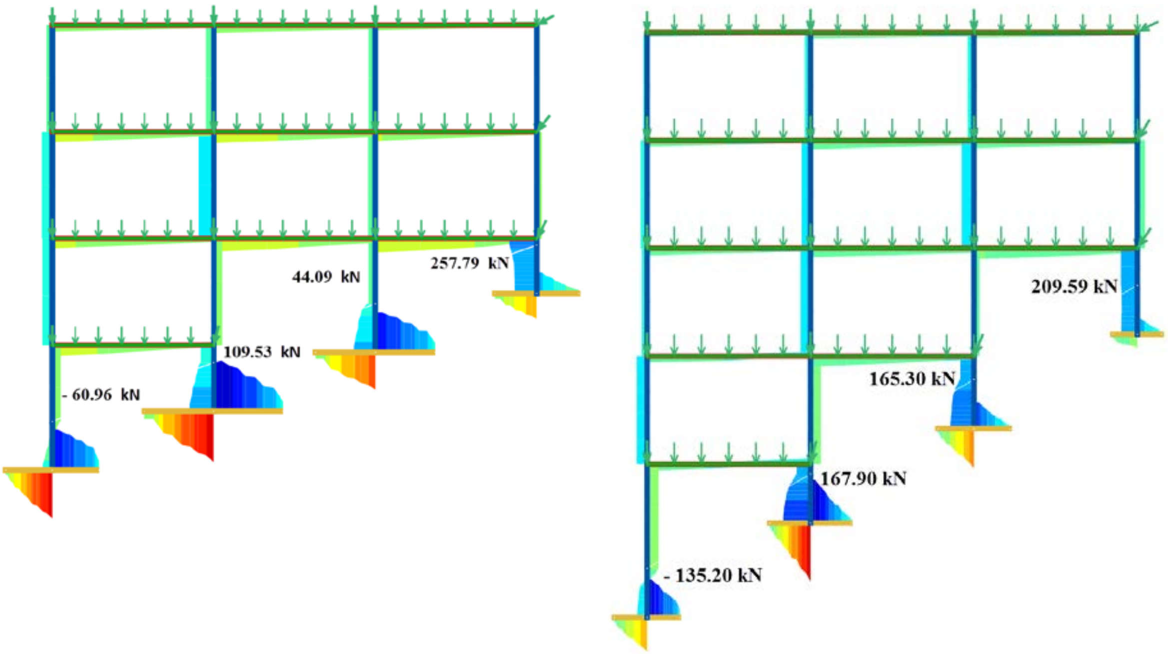



(b) (d)

**Fig. 10.** Displacement vectors showing failure surfaces of slopes under combined gravity and seismic load ($\alpha_h$ = 0.18 g) of a 2-storey building on: (a) 20º slope under integral building-foundation system; (b) 20º slope under independent foundations subjected to building loads; (c) 30º slope under integral building-foundation system; (d) 30º slope under independent foundations subjected to building loads.




(a) (c)




(b) (d)

**Fig. 11.** Shear force diagram for the 2-storey building under $\alpha_h = 0.18$ g on; (a) 20º slope with fixed base; (b) 20º slope considering coupled system; (c) 30º slope with fixed base; and (d) 30º slope considering coupled system.

### 4.4 Slopes under closely spaced multiple buildings

To study the effect of multiple adjacent buildings on slope stability under gravity and seismic loading, two and three adjacent buildings (either 2 or 4 storey tall) have been placed at equal distance from each other (with a clear distance between foundations of adjacent buildings as 5 m) on the same 20º and 30º slopes. Failure surfaces of the 20º and 30º slopes under three adjacent 2-storey buildings are shown in Fig. 12. It is evident from the figure that under gravity loading alone, the failure mechanism is global in 20º slope (see Fig. 12(a)), and local in 30º slope (see Fig. 12(c)). In local failure mechanism, the failure surface is formed by joining of the failure surfaces of individual foundations of the adjacent buildings. The variation in the FOS is insignificant under single and multiple 2-storey buildings subjected to gravity loading. Similar trend has also been observed for the considered 20º and 30º slope under the 4-storey single and multiple (three) buildings.

Variation in the FOS is significant for the 20º slope under single and multiple 2-storey buildings subjected to combined gravity and seismic loading. It has also been observed (Fig. 12(b)) that the critical failure surface in this case is close to global failure and that explains the effect of multiple buildings on FOS. Table 4 summarizes the FOS for all the considered cases under gravity and seismic loading. The table also indicates the failure modes in different cases, by the shade of the background of the corresponding cell. The cells with white background indicate a global failure, whereas the cells with light gray background indicate local failure of the slope. The cells with dark gray background indicate failure governed by the excessive displacement of the top-most foundation. These observations indicate that the number of buildings does not significantly affect the stability of the 30º slope, under gravity and seismic loading, where the slope fails locally below the building foundations. Whereas, the number of buildings, has some effect on the stability (< 10% reduction in FOS) of the 20º slope under gravity and seismic loading, where the slope fails with a deeper failure surface.

**Table 4.** FOS in different cases

| Slope | | 20º Slope | | | | | | 30º Slope | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No of storeys | | 2-Storey | | | 4-Storey | | | 2-Storey | | | 4-Storey | | |
| $\alpha_h$ (g) | | 0 | 0.12 | 0.18 | 0 | 0.12 | 0.18 | 0 | 0.12 | 0.18 | 0 | 0.12 | 0.18 |
| No. of Buildings | 0 | 2.29 | 1.67 | 1.46 | 2.29 | 1.67 | 1.46 | 1.99 | 1.55 | 1.38 | 1.99 | 1.55 | 1.38 |
| | 1 | 1.90 | 1.56 | 1.42 | 1.57 | 1.35 | 1.25 | 1.39 | 1.22 | 1.14 | 1.27 | 1.12 | 1.04 |
| | 2 | 1.82 | 1.50 | 1.32 | 1.56 | 1.30 | 1.19 | 1.38 | 1.22 | 1.14 | 1.27 | 1.12 | 1.04 |
| | 3 | 1.82 | 1.46 | 1.32 | 1.56 | 1.30 | 1.19 | 1.38 | 1.23 | 1.16 | 1.28 | 1.14 | 1.07 |
| | F* | 1.83 | 1.54 | 1.22 | 1.50 | 1.14 | 0.87 | 1.30 | 0.68 | 0.43 | 1.19 | 0.56 | 0.33 |

**'F' indicates individual foundations modelled without frame, and subjected to the fixed base reactions from the corresponding building.*

*The white background cells indicate global (deeper) failure mechanism (e.g. Fig. 10(a-b)); the cells with light gray background indicate local failure of the building-slope system (Fig. 10(c-d)); and the cells with dark gray background indicate failure governed by the excessive displacement of the top-most foundation (Fig. 9(c and f)).*

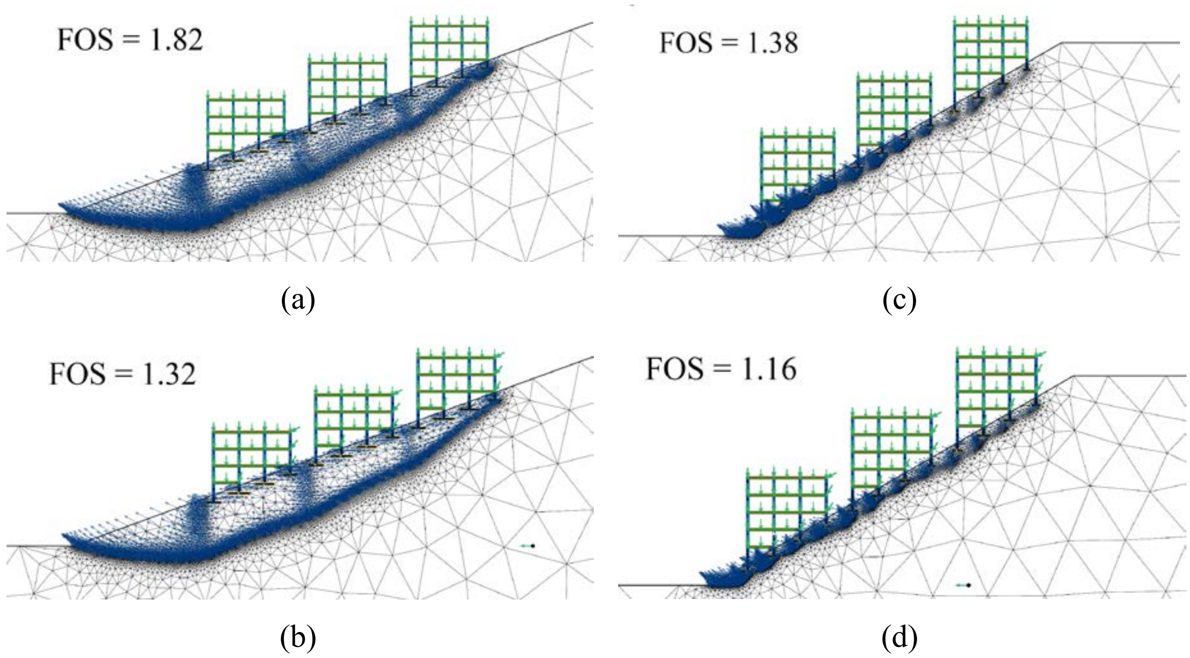



**Fig. 12.** Displacement vectors showing failure surfaces of slopes under multiple 2-storey buildings on: (a) 20º slope, $\alpha_h = 0$ g; (b) 20º slope, $\alpha_h = 0.18$ g; (c) 30º slope, $\alpha_h = 0$ g; and (d) 30º slope, $\alpha_h = 0.18$ g.

## 5. Conclusions

Extensive numerical studies have been performed to understand the stability of slopes under single and multiple adjacent foundations and buildings, subjected to gravity and seismic actions. In case of a slope loaded with single foundation, the critical failure surface of the slope changes from global to local, after a threshold load intensity. For all locations, sizes, and offset distances of foundations, considered in the present study, the FOS is relatively insensitive to the applied load intensity below the threshold value, but it reduces sharply with foundation load intensity increasing beyond the threshold value. Contrary to the effect of adjacent foundations in case of flat ground, where adjacent foundations result in an increase in ULI, the adjacent foundations on slopes result in a slight (2-19 %) decrease in ULI for all influence angles. This difference in the behaviour is due to asymmetric failure of soil below the foundations on slopes.

In case of slopes loaded with buildings, local failure mechanism occurs under gravity loading, by joining of the failure surfaces of individual footings. The integral action of building-foundation system yielded greater FOS than in case of independent foundations, subjected to the fixed base building reactions. The integral action resulted in redistribution of the foundation load and the whole system moved together along with a shallow soil layer. On the other hand, in case of multiple individual foundations, the displacement accumulated at the level of the bottom-most foundation. In case of multiple adjacent buildings on the slopes also, the failure surface was found to be formed by joining of failure surfaces of individual foundations, and hence there was no significant effect of the adjacent buildings on the FOS. It indicates that the number of adjacent buildings does not affect the stability of the slopes, significantly.

In case of seismic action also the behavior of footings and buildings on slopes has been observed to be largely unaffected by the adjacent footings and buildings. In case of independent analysis of footings subjected to fixed base reactions from a step-back building, the failure was governed by the top-most foundation, which was subjected to excessive lateral force due to large shear in the short stiff column. On the other hand, when the integral action of the building frame was considered, the lateral shear also got re-distributed and the slope-building system indicated much enhanced stability. In case of the $30^{\circ}$ slope considered in this study, the failure occurred locally below the building foundations, resulting in the FOS insensitive to the number of adjacent buildings. However, in case of the $20^{\circ}$ slope (which is a stiff clay site), the failure occurred along a deeper surface and the FOS indicated some (<10%) reduction with increase in number of buildings from one to three.

As the objective of the present study was to investigate the failure modes and FOS of stable slopes under multiple adjacent foundations and buildings, the effect of earthquake has been considered in a simplified manner by applying a seismic coefficient in the downhill lateral direction. Further, the effect of superstructure nonlinearity has been considered indirectly through use of response reduction factor and overstrength factor. A coupled nonlinear dynamic analysis of the building-slope system can provide some more information about the seismic behaviour of these systems, but the modelling is quite challenging and the computational time required is excessive. In the present study an attempt has been made to get an understanding of the failure mechanism with reasonable accuracy and computational effort.

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