Impact of transmitting boundaries on seismic behavior of building on slope under soil-structure interaction

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Abstract
The occurrence of seismic excitation across hilly region caused accumulation of stresses which resulted in failure of slope and structure. Recently, Syria and Turkey found failures of geostructures and slopes due to multiple earthquakes. This study investigates suitable height of building and slope stability considering soil-structure interaction (SSI). For this, building with varying heights were built on slopes. The finite element numerical modeling for SSI has been analyzed in ABAQUS with three transmitting boundaries namely viscous, Kelvin and infinite element boundaries. The investigation into the effects of boundary conditions on varying peak ground acceleration (PGA), amplification factor and stresses in a slope-building system indicates that horizontal displacement of slope surface increases proportionally with height and inclinations.

The findings emphasize a noteworthy decrease in response ranging from 45-56% at waist and 50-60% at crest in comparison to toe of slope when infinite boundaries are considered. Additionally, flexible base condition in the building system leads to 75% increase in the duration of vibration, attributed to height of structures in hilly areas dependent on slope characteristics. The study recommends mid-rise building height (G+5) as an optimal choice for construction in high-inclination slopes of the Himalayan hills.

Keywords: Soil-structure interaction (SSI), Boundary conditions, Slope, earthquake loading, Slope building.

Introduction

An increase in population consequently increases the migration of people from urban flat area to sloping ground. Buildings on slopes are usually a common practice in hills due to unavailability of flat land. The buildings constructed on the slopes lead to certain consequences under seismic excitation such as natural calamities, slope failure and risky[12]. Recently Morocco and Sikkim-Darjeeling highway observed failures of buildings and slopes respectively (Figure 1). The human or natural induced activities may be precarious for sloping terrains since these activities are associated with the vibration in soil resulting in seismic waves. The major challenges are mitigation of waves at boundary of slope-structure. Many researchers have conducted the study on mitigation of seismic waves at boundary[1,3,42]. However, a very few investigation of building kept on face of slope have been made under the seismic excitation[24,34].

In recent studies, it has been found that implementation of proper boundary conditions at boundary of soil-slope system was helpful to mitigate waves at boundary[23,24]. These aspects are of utmost importance and necessitate a comprehensive examination of boundary conditions to ensure the stability of the soil-slope and to prevent failures. The study and implementation of proper boundaries have motivated authors to study the effect of seismic excitation on stability of slope-building.

In this regard, buildings built on slopes require critical attention on surrounding of buildings and its interaction with soils. For this, soil-structure interaction (SSI) analysis can be performed for interaction behavior of soil-slope and buildings.

SSI is a complex phenomenon since its alter the responses of soil as well as structure. SSI may be beneficial specially when structure is placed on slopes under seismic condition[24]. The seismic condition of slope with buildings must be implemented with proper boundaries conditions so that responses of buildings, stress accumulation in the vicinity of slopes and reflection of waves can be absorbed or transmitted from the SSI system.

The sloping area subjected to seismic excitations may be prone to several factors that contribute to instability of slopes, safety of buildings on slopes and accumulation of stress/strain. Quantifying instability of both structures and slopes is essential to assure safe and cost-effective design when constructing on slope terrain. To ensure safe structural design on sloped surfaces, it is necessary to evaluate how the structure and soil both respond to variations in the number of storeys. Numerous methodologies have been employed to mitigate instability in structures[7,18,38,44]. Past research indicates that leveraging advancements in computational tools can contribute to safe and cost-effective construction in sloping areas as emphasized in recent studies[23,24,34,35,48].

The novelty of this study is to simulate the real scenario of buildings on slope (i.e. building constructed on face of slope) considering implementation of proper boundaries.

https://doi.org/10.25303/175da09023

Figure 1: Recent failures at Morocco and Sikkim-Darjeeling Himalayan region

In this respect, effects of seismic excitation on low-md-high rise buildings (G+3, G+5 and G+7) in seismically active slope were studied and instability of building and soil slope are investigated in this study. To find out proper boundaries for soil-slope-building system, three boundary conditions were imposed. The response of high rise buildings and behavior of slopes with PGA, effect of SSI and various boundaries have been investigated. The three boundaries: viscous boundary (VB)[30], Kelvin element boundary (KB)[32] and infinite element boundary (IB)[4] have been used in this study.

Review of Literature

Very recently the series of seismic excitations have been felt in the Nepal and India. The detailed survey on SSI is urgently needed. The instability of slope and its treatment with proper boundaries conditions have been surveyed through literature. Paul and Kumar[33] presented the slope stability analysis considering the various configurations of structural load on slope. The traditional method was compared with numerical analysis under SSI effect. It was concluded that the factor of safety reduced under earthquake loading.

Kourkoulis et al[17] carried out numerical modelling for the effect of types and position of foundation on slope. The earthquake loading on precarious slopes has been imposed to observe the failure surface formation, gap to the foundation and foundation soil etc. The raft rigid foundation was recommended for keeping slope safe with respect to high impact of earthquake excitation.

Fathi et al[10] assessed dynamic behavior of historic building of Arge-Tabriz with soil-foundation-structure interaction. The analysis was performed under SSI and fixed base condition. It was concluded that the building was stable under gravity and real behavior was observed with SSI.

Far[8] adopted realistic numerical model for the most precarious and challenging issue with soft soil under dynamic load considering SSI. It was recommended that the SSI is essential for the structure on soft soil and non-linear analysis must be performed with real behavior of building on soft soil. Kumari and Sawant[26] performed liquefaction behavior of soil under seismic excitation by implementing the small strain theory with transmitting boundary. The suitability of transmitting boundaries has been recommended for the liquefaction behavior of soil under seismic loading.

Kumar and Mishra[19] conducted SSI studies of building on various foundation size of isolated, mat and pile on shake table. The foundation with large depth resulted in less lateral movement. Kumar and Mishra[20] evaluated the characteristics of structure under excavation effect considering SSI. For this, the building was modelled on shake table. The behavior of building was observed precarious on account of excavation near the structure.

Kumar and Kumari[21] recently studied geostructures like nuclear reactor building on account of SSI. The artificial boundary was imposed on the reactor building soil mass to simulate the behavior of building and soil under dynamic load. More emphasis was recommended on the essential boundaries to obtain the actual response to safer and efficient design. The seismic analysis for buildings near shallow slope was simulated in PLAXIS three dimensional (3D) under slope-foundation-structure interaction by Fatahi et al[10]. The mid-rise moment resisting building adjacent to the crest of slope was considered. The large deformation was observed in the slope when the building was placed near the slope and slope became more susceptible to instability.

The 3D seismic nonlinear analysis of buildings near slope considering topography-structure-soil-structure interaction was studied by Shamsi et al[38]. The two different soil deposits as per Eurocode with different slope inclination and various slope heights have been used for the analysis of 15-story steel moment resisting building near slope crest. The FE analysis was used to evaluate the impacts on structures. It was recommended that the topography affects the neighbouring buildings depending on the soil types. It was also concluded that the SSI showed the beneficial effects on slope buildings.

The structure build on slope may encounter the settlement issue as studied by Salih and Laman[36]. The study was conducted for the surface footing on slope and guidelines were recommended. It was observed that the crest distance and buried structure near slope affect the bearing capacity of soil. The seismic behavior of structure on varios soft soil has been investigated for the assessment of vulnerability of structure considering SSI by Tahghighi and Mohammadi[43].

The numerical investigation was performed under finite element model. It was concluded that the fragility and performance of structure on rigid base must be verified under SSI. It was also observed that the role of SSI should be imparted in the safety of building under the interaction of soil and building. Recently the fragility analysis of building on slope has been studied considering the coupled building-slope system under seismic excitation by Raj et al[34]. The interest of study was to analyse the additional factors like topography effect, building on slope face, multiple adjacent buildings on slopes which affect the slopes obviously. The Indian and Chinese hilly region slope were studied for fragility analysis. It is concluded that the SSI must affect the fragility analysis of building on slope system.

The SSI considerably affects the behavior of building caused by seismic excitation and specially the building on slope or near to crest is much affected by the amplification of ground motion by Shabani et al[37]. The non-linear 3D numerical analyses were performed on buildings considering the buildings were at same distance from crest and toe. The distance of building was assumed as height of building. It was concluded that the topography and SSI significantly affect the response of building.

The detailed study of building found on hill slopes has been investigated by considering the SSI and geological layer surface inclinations by Skuodis et al[41]. It was also concluded that surface inclination of natural soil layer observed higher inclination with technogenic soil layer. A cut slope stability issue has been rectified using centrifuge modeling of soil nailing technique by Baziar et al[2]. The amplification of soil was considered for the non-linear analysis and it was concluded that the centrifuge modeling may be a realistic method over conventional method. The location of footing was displaced by an amount of 0.625 %.

Further, centrifuge modeling tests were conducted on three slopes under the mutual effect of bedrock and drawdown by Luo et al[29]. An image-based system was used for the progressive failure surface and deformation in slopes. It was concluded that the presence of bedrock reduces the slope's ductility during drawdown compared to a slope without bedrock. It was recommended that the bedrock alters the failure characteristics of the slope by impacting the way deformation is localized. The beneficial effect of seismic SSI has been further assessed for the high rise buildings by Zhang and Far[48].

The various parameters such as types of foundation, height-width ratio, soil types etc. have been considered for the study of soil-foundation-structuure model. The pile foundation was assessed with said parameters and it was found that SSI effect was detrimental.

Recently the most important parameters of building on soil under seismic excitation have been assessed by considering the topography interaction with SSI by Shamsi et al[39]. The inelastic behavior of moments resistant frame building of 5, 10 and 15 storey buildings has been studied with consideration of topography SSI. It was concluded that the presence of topography can lead to a significant alteration in the seismic behavior of 5-story low-rise structures.

The majority of research in this field has primarily focused on investigating the nonlinear dynamic response of slopes, often neglecting the presence of structures on the slopes faces[31]. Few researchers have delved into the instability of slopes when structures were present on the slope's face, taking into account the impact of SSI and employing measures to mitigate the reflection of seismic waves from the boundaries. Some researchers have incorporated a VB boundary condition to model the behavior of slopes with structures[16,28].

Notably, Fatahi et al[10] examined scenarios where buildings were positioned at various locations on the crest of a slope, considering only the VB boundary approach. Existing literature on SSI has addressed the issue of boundary conditions for reflected seismic excitation, but these discussions have often centred on elementary boundaries[35] and VB boundaries[9].

Problem statement: A slope of 100 m height with three different inclination 1:1, 1:1.3 and 1:1.6 was taken for the stability of free slope and building on slope. The properties of soil slope, building components beam, column and foundation are shown in table 1 and 2 respectively. The instability of slopes under SSI effect was studied. The three different buildings with isolated foundation width 2 m were used to analyse the instability of slopes. The interaction of building on straight and steps slope subjected to seismic excitation under three boundary conditions was examined. The modeling of slope with SSI has been performed with various inclinations as shown in figure 2. For brevity, 1:1.3 one step slope has shown only in figure 3.

Material and Methods

The finite element method is a versatile and powerful numerical technique that offers many advantages over conventional method for studying the dynamic SSI phenomenon in soil-slope systems under plane strain conditions. However, the compatibility requirements with plain strain condition are more feasible in analysis of behavior of slope and mesh generation.

The engineering approximation, hand calculations, influence of complicated loading and boundaries etc. can be more flexible, adaptable and capable to handle complex geometries, material properties, boundary conditions and dynamic analysis making it a preferred choice for investigating and understanding the behavior of these systems using the finite element method. However, in current study, this method is adopted for the analysis.

The seismic wave induced in SSI system should be completely absorbed/refracted at boundary. The reflection of waves may cause disruptive effect on building-slope response. Therefore, boundary must be chosen as per appropriateness of system. The suitability of boundaries has been chosen amongst viscous, Kelvin and infinite boundaries.

https://doi.org/10.25303/175da09023

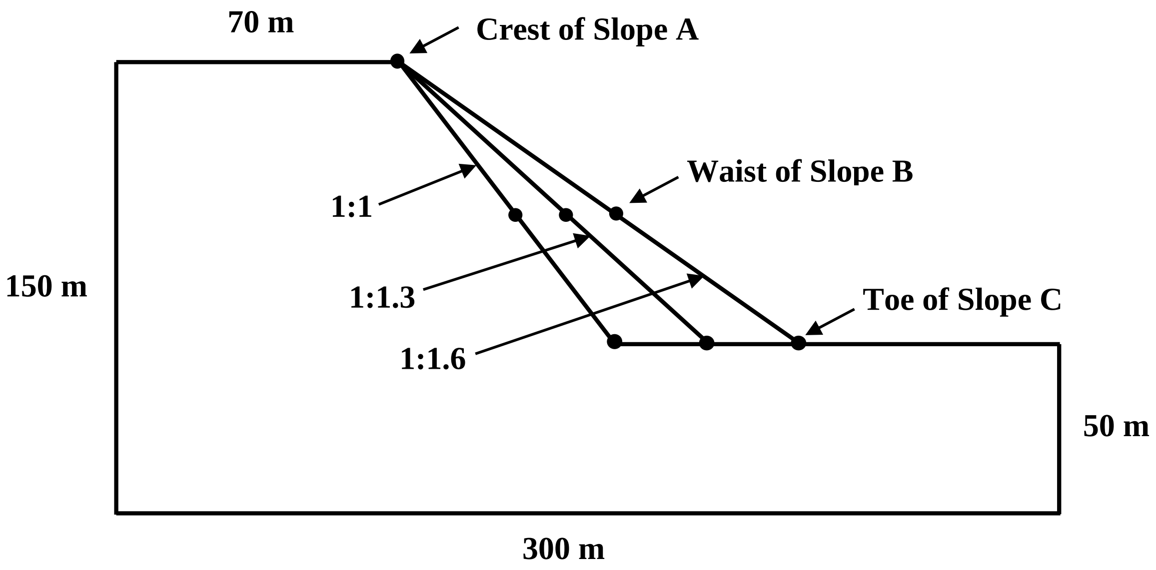


Figure 2: Inclinations of free straight Slope[5]

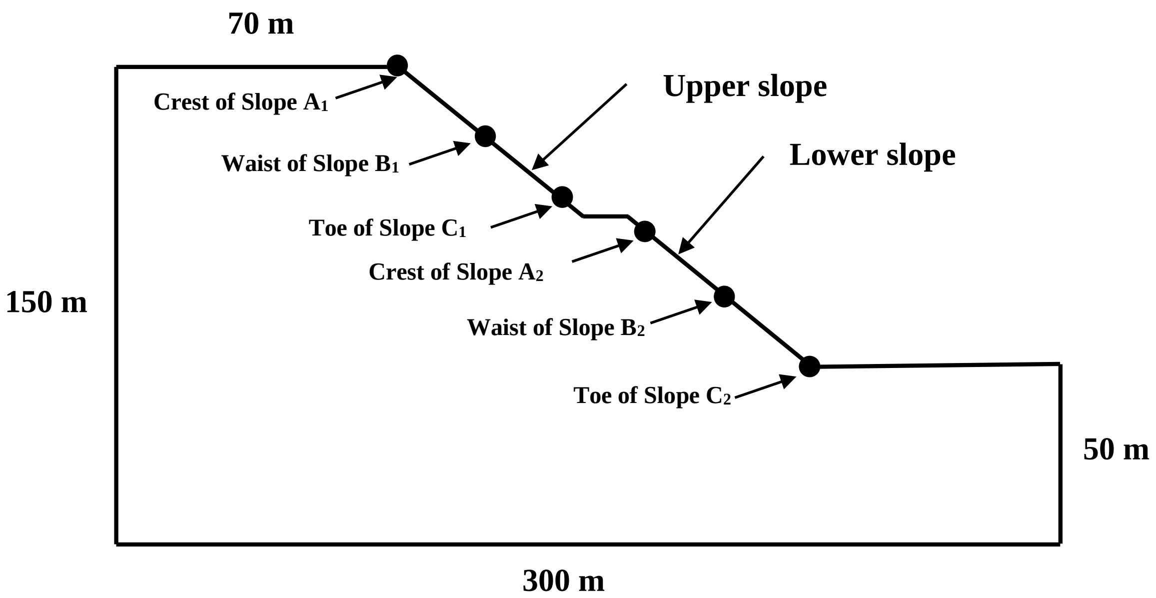


Figure 3: One step free slope of inclination 1:1.3

Table 1
Material properties of soil[5]

Silty clay	
Soil elastic modulus	41x 10^6 N/m^2
Poisson's value	0.35
Density	2150 kg/m^3
Damping (soil and concrete)	5%
Rayleigh damping co-efficient α and β	0.009155 and 0.243445
Dilation angle	0.1
Shear modulus	15.18 x 106 N/m^2
Cohesion	22000 N/m^2
Friction angle	17^0
Slope inclination	1:1, 1:1.3, 1:1.6
Slope type	Straight, one step

The straight and step slope were used to place on different height of buildings as discussed (see Figure 2-3) respectively. The position of foundation was at a depth of 2 m below the soil slope and remains constant in all cases.

Table 2
Material properties of beam, column and foundation

Material parameters for structural members	
Beam member size	0.25 m × 0.5 m
Length of beam	5 m
Column member size	0.5 m × 0.5 m
Each column height	3 m
Young's Modulus of concrete	25×10^9 N/m^2
Poisson's value	0.15
Rayleigh co-efficients	0.0701 and 0.0303
Foundation size	2 m × 2 m
Concrete density*	2500 kg/m^3
* Density 25 kN/m	

The details description of boundary condition with finite element method software has been discussed by Kumar et al[24]. For the present study, a 2D finite element analysis with 8-noded quadrilateral element has been implemented for the analysis of SSI phenomenon for building on slope assuming plane strain condition under dynamic load.

Eight noded quadrilateral element: The choice of an 8-noded quadrilateral element is suitable for the analysis of SSI, especially when dealing with complex geometries and a need for high precision. It offers advantages in terms of shape flexibility, precision and reduced mesh sensitivity.

However, users should be aware of the potential for increased computational costs and the need for careful mesh design to address limitations such as shape distortion.

The shape functions associated with 8-noded isoparametric element is shown in equation 1:

$$x = \sum_{i=1}^{n} N_i x_i \quad ; \quad z = \sum_{i=1}^{n} N_i z_i \qquad (1)$$

where n is total number of nodes in element, x_i and z_i are the co-ordinates and N_i are the shape function associated with node i.

The nodal displacements u and w with shape function are expressed in equation 2:

$$u = \sum_{i=1}^{n} N_i u_i \quad ; \quad w = \sum_{i=1}^{n} N_i w_i \qquad (2)$$

The details of the eight node element are well documented in literature on finite element analysis, therefore the derivation of shape functions is not discussed. The shape functions associated with each of the element nodes in the natural co-ordinate system (ξ, η) for the node numbering as shown in figure 4 are given as follows:

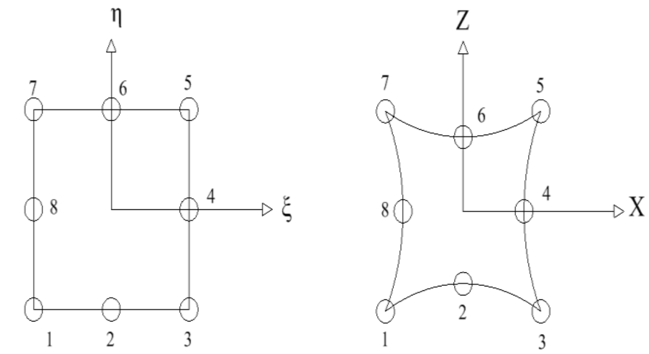


Figure 4: Eight node continuum element

The shape function matrix for the solid phase is:

$$N_e(\xi,\eta) = \begin{bmatrix} N_1 & 0 & N_2 & 0 & \dots & \dots & N_8 & 0 \\ 0 & N_1 & 0 & N_2 & \dots & \dots & 0 & N_8 \end{bmatrix} \qquad (3)$$

The strain can be obtained from equation 4:

$$\varepsilon_x = \frac{\partial u}{\partial x}; \qquad \varepsilon_z = \frac{\partial w}{\partial x} \quad ; \quad \gamma_{xz} = \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \qquad (4)$$

The relation between the derivatives in the natural (local) and cartesian (global) coordinate systems can be expressed by the chain rule of differentiation as:

If φ is function of $\{x, z\}$, then,

$$\frac{\partial \varphi}{\partial \xi} = \frac{\partial \varphi}{\partial x}\frac{\partial x}{\partial \xi} + \frac{\partial \varphi}{\partial z}\frac{\partial z}{\partial \xi} \text{ and } \frac{\partial \varphi}{\partial \eta} = \frac{\partial \varphi}{\partial x}\frac{\partial x}{\partial \eta} + \frac{\partial \varphi}{\partial z}\frac{\partial z}{\partial \eta} \qquad (5)$$

In the matrix form, it is:

$$\begin{Bmatrix} \frac{\partial \varphi}{\partial \xi} \\ \frac{\partial \varphi}{\partial \eta} \end{Bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial z}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial z}{\partial \eta} \end{bmatrix} \begin{Bmatrix} \frac{\partial \varphi}{\partial x} \\ \frac{\partial \varphi}{\partial z} \end{Bmatrix} = [J] \begin{Bmatrix} \frac{\partial \varphi}{\partial x} \\ \frac{\partial \varphi}{\partial z} \end{Bmatrix} \qquad (6)$$

The 2×2 matrix in the above equation is known as the Jacobian matrix (J) and derivatives in the global co-ordinate system can then be represented as:

$$\begin{Bmatrix} \frac{\partial\varphi}{\partial x} \\ \frac{\partial\varphi}{\partial z} \end{Bmatrix} = [J]^{-1} \begin{Bmatrix} \frac{\partial\varphi}{\partial\xi} \\ \frac{\partial\varphi}{\partial\eta} \end{Bmatrix} = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{bmatrix} \begin{Bmatrix} \frac{\partial\varphi}{\partial\xi} \\ \frac{\partial\varphi}{\partial\eta} \end{Bmatrix} \quad (7)$$

where Γ_{ij} corresponds to the term in the i^{th} row and j^{th} column of inverse of the Jacobian matrix (J).

Using equations (4) to (7), the relation between strains and nodal displacements is expressed as:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_z \\ \gamma_{xz} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial w}{\partial z} \\ \frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \end{Bmatrix} = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} & 0 & 0 \\ 0 & 0 & \Gamma_{21} & \Gamma_{22} \\ \Gamma_{21} & \Gamma_{22} & \Gamma_{11} & \Gamma_{12} \end{bmatrix} \begin{Bmatrix} \frac{\partial u}{\partial\xi} \\ \frac{\partial u}{\partial\eta} \\ \frac{\partial w}{\partial\xi} \\ \frac{\partial w}{\partial\eta} \end{Bmatrix} \quad (8)$$

$$\begin{Bmatrix} \frac{\partial u}{\partial\xi} \\ \frac{\partial u}{\partial\eta} \\ \frac{\partial w}{\partial\xi} \\ \frac{\partial w}{\partial\eta} \end{Bmatrix} = \begin{bmatrix} \frac{\partial N_1}{\partial\xi} & 0 & \cdots & \frac{\partial N_n}{\partial\xi} & 0 \\ \frac{\partial N_1}{\partial\eta} & 0 & \cdots & \frac{\partial N_n}{\partial\eta} & 0 \\ 0 & \frac{\partial N_1}{\partial\xi} & \cdots & 0 & \frac{\partial N_n}{\partial\xi} \\ 0 & \frac{\partial N_1}{\partial\eta} & \cdots & 0 & \frac{\partial N_n}{\partial\eta} \end{bmatrix} \{\delta\}_e \quad (9)$$

Combining above two equations (Equations 9 and 10), we have:

$$\{\varepsilon\} = [B] \quad \{\delta\}_e \quad (10)$$

Sub-matrix $[B_i]$ for node i is given by following equations:

$$[B_i] = \begin{bmatrix} \Gamma_{11}\frac{\partial N_i}{\partial\xi} + \Gamma_{12}\frac{\partial N_i}{\partial\eta} & 0 \\ 0 & \Gamma_{21}\frac{\partial N_i}{\partial\xi} + \Gamma_{22}\frac{\partial N_i}{\partial\eta} \\ \Gamma_{21}\frac{\partial N_i}{\partial\xi} + \Gamma_{22}\frac{\partial N_i}{\partial\eta} & \Gamma_{11}\frac{\partial N_i}{\partial\xi} + \Gamma_{12}\frac{\partial N_i}{\partial\eta} \end{bmatrix} \quad (11)$$

$$\{\sigma\} = \begin{Bmatrix} \sigma_x \\ \sigma_z \\ \tau_{xz} \end{Bmatrix} = [D] \begin{Bmatrix} \varepsilon_x \\ \varepsilon_z \\ \gamma_{xz} \end{Bmatrix} \quad (12)$$

where σ_x, σ_z and τ_{zx} are three stresses.

The constitutive matrix considering isotropic, homogeneous elastic material under plane strain condition is shown in equation 13:

$$[D] = \frac{E}{(1-\mu)(1-2\mu)} \begin{bmatrix} 1-\mu & \mu & 0 \\ \mu & 1-\mu & 0 \\ 0 & 0 & \frac{1-2\mu}{2} \end{bmatrix} \quad (13)$$

Equation (12) can be written in the abbreviated form as:

$$\{\sigma\} = [D]\{\varepsilon\} = [D][B]\{\delta_e\} \quad (14)$$

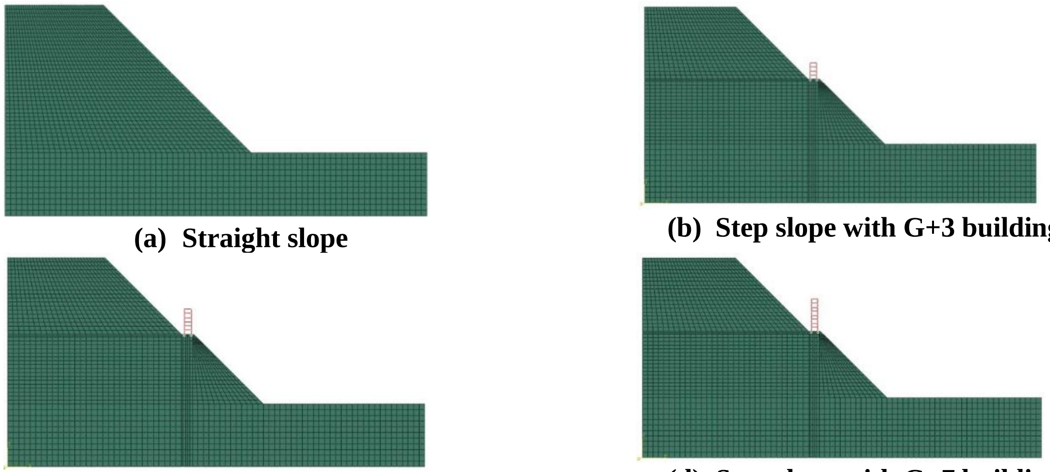
Numerical Modeling: The study significantly uses finite element numerical modelling approach for SSI behavior on slopes. ABAQUS, a finite element tool was used for modelling and analysis. The constitutive behavior of material was needed to assign the material properties in this method. For this, soil was modelled with Mohr-Coulomb with associated flow rule. Behaviour, PGA amplification factor, stress contour for different slopes with varying building frames have been estimated. The boundary condition analyses depend on the nature of analysis of SSI considered. The step by step analysis has been conducted as frequency and dynamic analysis.

The meshing process involves dividing a complex geometry into smaller elements using mesh generation techniques based on the compatibility of its connecting elements and the convergence of process. The structured and sweep mesh techniques have been used in the analysis[13,47]. The slope part of model was done with sweep method so that the similar kind of element (quadrilateral element) can be created in the model to maintain the compatibility.

However, other method of meshing leads to generate two different shapes of element. The wave propagation principles based on the frequency, wavelength and shear wave velocity relation were used for the size of mesh[45].

For the fastest convergence and realistic behavior of accumulated stress and strain within the SSI problem in plain strain, quadrilateral elements has been considered for both soil-foundation model[23]. For beam and column, 3-node quadratic element has been used in plane strain condition because quadratic elements are typically used for better accuracy in modeling complex deformations depending on the specific geometry and loading conditions.

The slope-buiding analyses started with the combination of ground with 3-5-7 floor buildings. The slope-building model was built on straight and one step slopes (Figure 5). Three points of interest A, B and C on slope-building model as toe, waist and crest respectively have been identified for the response of SSI system[7].



(a) Straight slope

(b) Step slope with G+3 building

(c) Step slope with G+5 building

(d) Step slope with G+7 building

Figure 5: Straight and step slope for 1:1

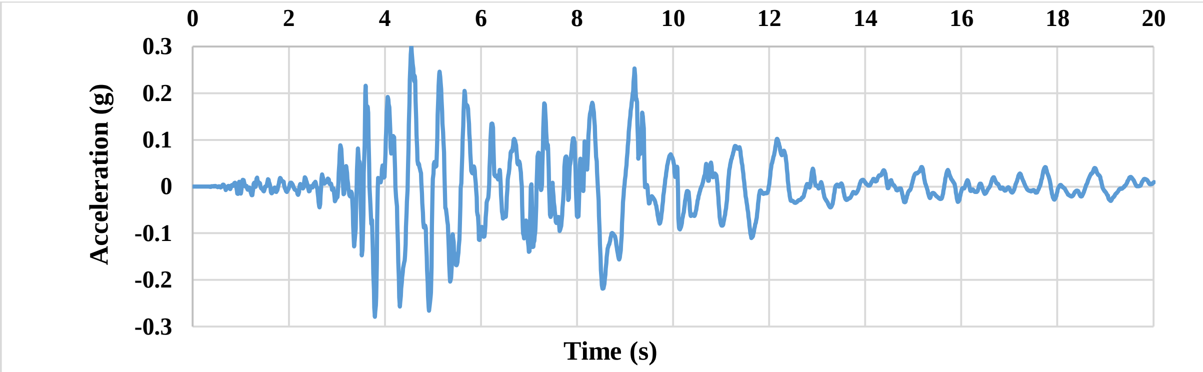


Figure 6: Northridge (1994) earthquake acceleration-time history

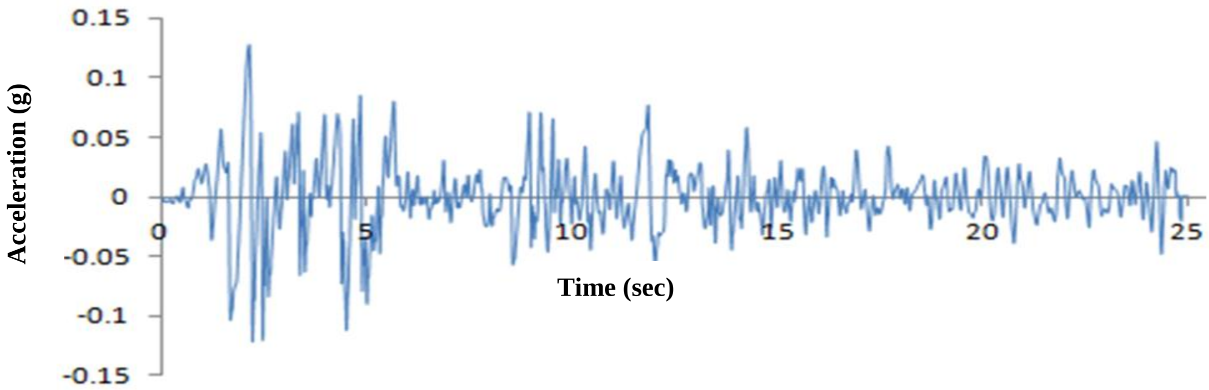


Figure 7: Actual seismic excitation applied at base

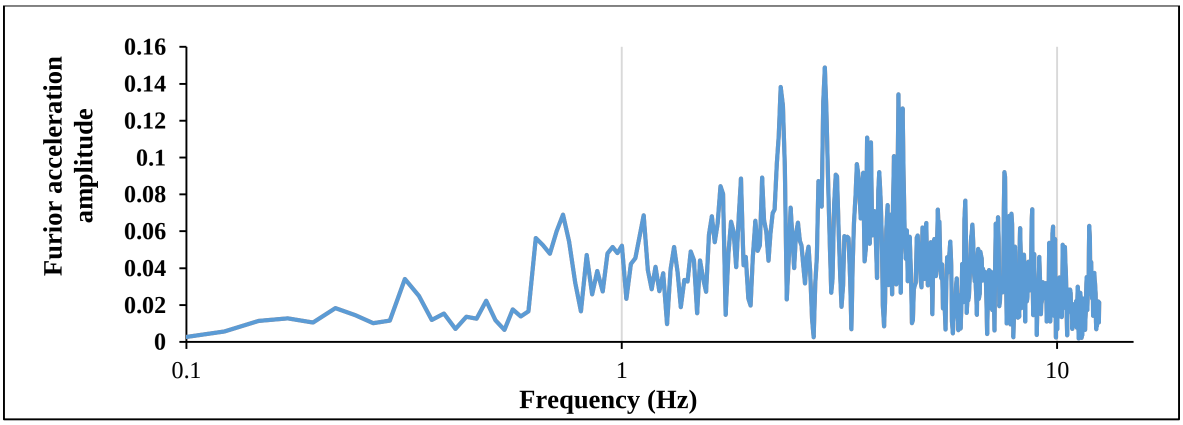


Figure 8: Variation of Fourier acceleration amplitude with frequency

Input motion: This seismic excitation of Northridge (1994) earthquake was used first time in world to test large scaled test in the densely constructed area of buildings. In this study, the excitation received at Northridge was used as input motion for the model analysis (Figure 6). The PGA of 0.3g was received at actual site, however, current study has different soil strata. The PGA of 0.13g was found after de-convolution [6] and this was directly implemented in this study (Figure 8)[25]. The frequency was determined in siesmo-signal and its predominant value was reported 2.32 Hz corresponding to 0.13g PGA as illustrated in figure 8.

Results

The stability of buildings on slope was analysed for three boundaries conditions under the seismic excitation considering SSI. The effects of energy dissipation, amplification factor for free and slope with structure were discussed. Responses for varying PGA and effect of different boundaries conditions are also presented here.

Time Period of SSI system: The SSI analysis must be studied with fixed and flexible base of building[20-23]. Fixed and flexible base comprises of equivalent and varying stiffness for both soil and foundation. The height of building is one of the most prominent parameters for providing flexibility of the SSI system. The vibration causes a dynamic motion in the system. However, this vibration can lead to the collapse of building particular in case of the ground motion. Here, the height of structure inclusion with the soil has been studied for observing the behavior of building on slopes.

The mode shape was obtained with the consideration of linear perturbation analysis. This shapes shows the energy dissipation in the dynamic system[23,24,46]. The effect of height on building especially on hill slopes was observed. The effectiveness of SSI can be observed for the various heights of buildings in figure 9. The maximum dissipation of energy can be represented by the maximum number of deflected shapes. The G+(3-5-7) buildings have been shown in the figure 10 and obviously the taller buildings will have large energy dissipation. The desired result was obtained for the increased height of building.

Further, the flexibility condition in SSI system was considered to obtain the fundamental vibration of SSI system. The vibration value in free vibration was 25 % with the fixed base condition. However, this was 3 times larger than in case of flexible base condition. These obtained results recommend that the SSI must be considered for such kind of analysis in the geotechnical problems.

Amplification response without structure on slope: The effects of applied seismic motion on slope with and without structure were studied. The amplification of input motion was carried out for slope model with three boundaries. The result was validated with FLAC3D[5]. The response was calculated with interested nodes and it was found that the amplification is almost near to FLAC3D results with viscous boundary. The amplification was further reduced with the boundaries used in the current study.

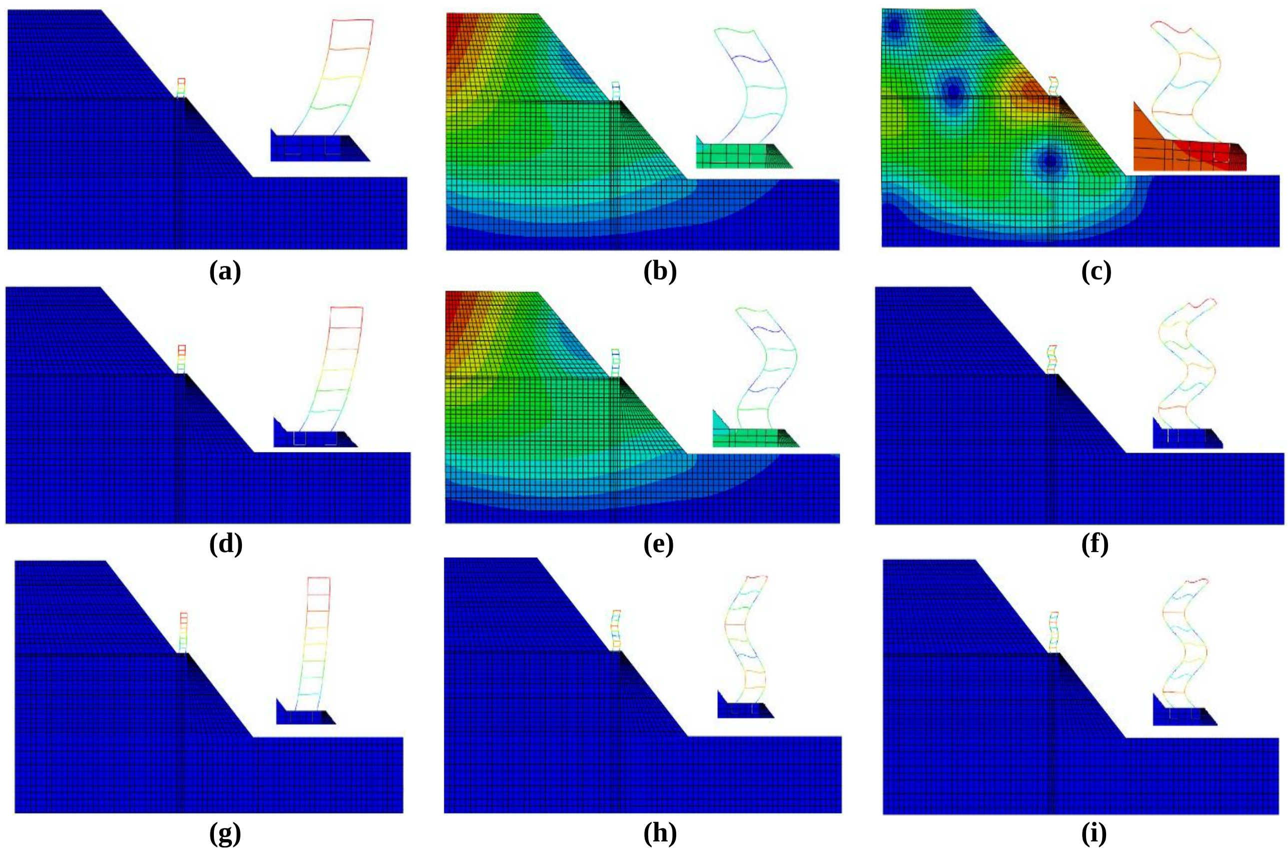


Figure 9: Effect of height of building on slopes

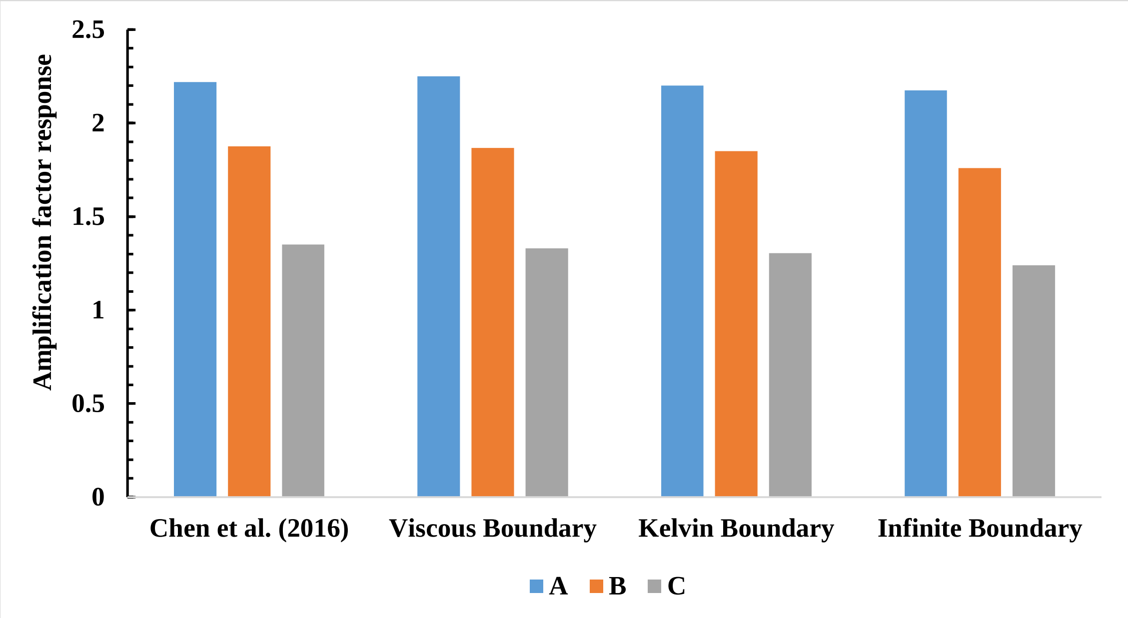


Figure 10: Variation of amplification response for slope 1:1

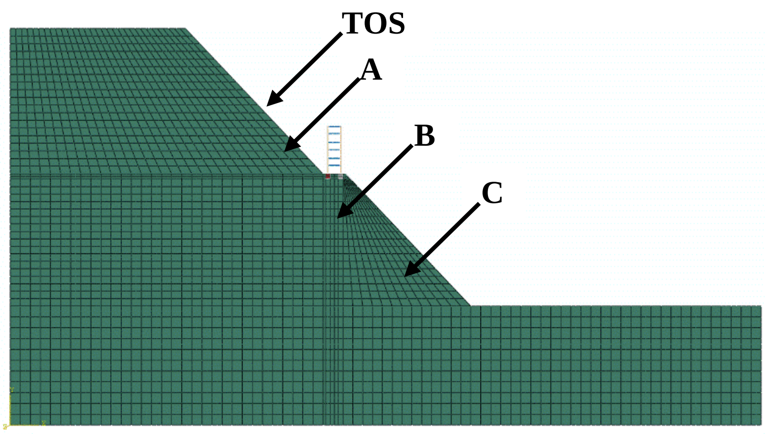


Figure 11: PGA amplification nodes in SSB system

Figure 10 shows the impact of amplification with boundaries on various slope inclination. The amplification was found increased with nodes C-B-A consistent with slope 1:1.3 and 1:1.6 (for brevity). The similar kind of study on landslides of slopes of three different inclinations was performed by Lenti and Martino[27]. The amplification effect increased with slope inclination. This validates the result of current study as amplification effect increases as slope inclination increases. The amplification was found large with high inclination, however, the reduction in amplification was consistent with boundaries used in present study. The reduction was observed more than 30% and 40% with high inclination with KB and IB boundaries respectively. This shows the efficacy of current boundaries to implement these boundaries for more stability of slopes.

Amplification response with structures: The study of inertial effect of SSI has been carried with placing the different height of structures on various slope inclinations. Here, a building on step slopes has been shown for describing the amplification and behavior of slopes and buildings under SSI (Figure 11). The additional nodes at building top (TOS) were considered in spite of others nodes as discussed previously.

The previous study found that the input motion was amplified by 2.8 to 4.5 times while structure was on slope under viscous boundary[49]. The current study validates this results as obtaining the amplification of input motion by 2.7 to 5 times of input motion as shown in table 3.

Further same trend was obtained with structures placed on the slope with viscous boundary[22]. The response of amplification with height of slope was found similar as slope was without structure.

It was almost 2 times less amplified when we put the structure on slope. This is one of the essential requirements to study SSI of buildings on slopes. This variation at toe of slope and top of building was nearly 9 to 20 times than input motion. The height and vibration period of SSI system were implemented in this study and it was found that the mid height building on slope showed large reduction of amplification.

Table 3
Amplification of slope with structure

Boundary condition →	VB			KB			IB		
Rise of building → Nodes ↓	Low	Mid	High	Low	Mid	High	Low	Mid	High
Slope 1:1									
TOS	6.2	6.4	6.7	6.1	6.2	6.41	5.12	5.89	5.98
A	4.9	5.1	5.31	4.81	4.75	5.48	4.25	4.52	4.87
B	3.2	3.4	3.64	2.98	3.02	3.98	2.95	3	3.56
C	2.9	2.95	2.98	2.81	2.87	3.01	2.35	2.48	2.78
Slope 1:1.3									
TOS	5.95	6.12	6.48	5.78	5.95	6.25	4.97	5.35	5.73
A	4.58	4.86	5.12	4.59	4.65	5.24	4.16	4.29	4.68
B	3.09	3.15	3.26	2.76	2.84	3.76	2.43	2.84	3.47
C	2.52	2.61	2.75	2.31	2.32	2.99	2.12	2.42	2.62
Slope 1:1.6									
TOS	5.78	6.01	6.7	5.59	5.88	6.19	4.84	5.26	5.65
A	4.39	4.62	5.31	4.27	4.53	5.08	4.01	4.19	4.57
B	3.01	3.08	3.19	2.68	2.81	3.57	2.21	2.72	3.38
C	2.28	2.35	2.67	2.21	2.29	2.76	1.98	2.18	2.46

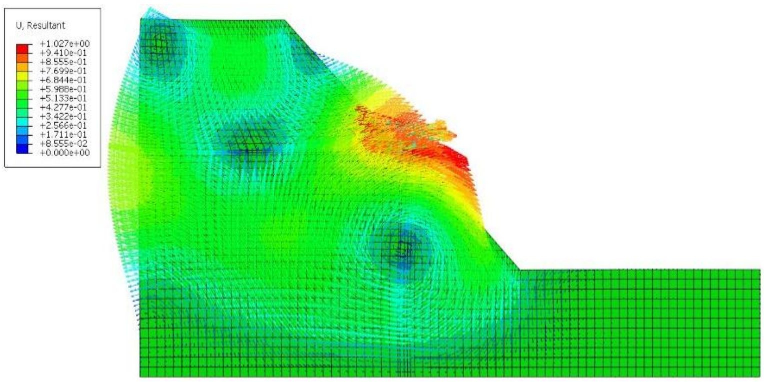


Figure 12: Behavior of slopes on account of foundation soil interaction

This variation was consistent with the boundaries also. Thus, the mid-height (G+5) building was found suitable and this validates the clause 7.6.1 of IS code 1893. The validity of this result may confirm the collapse of building during 2013 earthquake at Sikkim and Nepal[40]. Stable slope with various boundaries was not affecting much variation in responses and have experienced the lesser reduction in responses due to the provision of proper boundaries and consideration of SSI. The stability of slopes with buildings can be judged in terms of reduction in amplification. The less height building was found with maximum reduction. Moving from lesser to high slope with structure, there was an increase in this amplification factor. However, this reduction was observed very less with slope 1:1 and with mid height building. Thus have the stability of mid height building remains stable on high inclination[15,23,37,38].

Deformation in buildings on step slopes: To ensure the stability of structure on slopes, the deformation and accumulation of stress have been further analysed. The step-slopes with structures were considered for the propagation of stress and deformation around the foundation, building and in slope mass (Figure 12). The deformation of slope with and without building has been assessed and it was found that the deformation was larger in case of slope with building. The creation of plastic zone in the vicinity of foundation may cause this behavior in slopes. Thus, it is recommended that the foundation interactions with soil and buildings are also important aspects with SSI[23].

The stress analysis was conducted on low-mid-high rise buildings on slopes on account of boundary conditions. The insignificant reflection of waves at boundaries has been seen in the case of Kelvin boundaries. The partial reflection was observed in the case of viscous boundaries. However, infinite element boundaries have approximately transmitted seismic waves very far from the boundaries. The impact of boundaries on slope-building has been analysed with various heights of the building as shown in figure 13. The propagation of stress under viscous boundary was initiated at the lower slope and the stress concentration can be observed at upper slope also. The concentration was more intense near the foundation (Figure 13a).

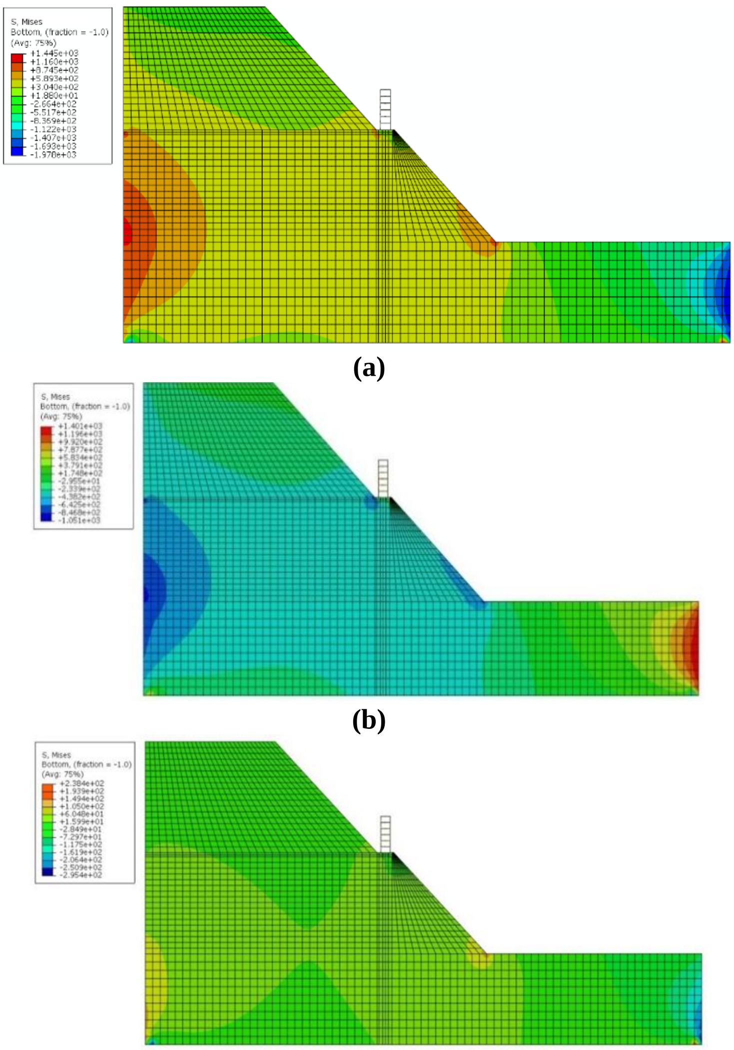
The Kelvin boundary has reduced the response by 100 times lesser than the viscous boundary at both lower and upper slope (Figure 13b). There is insignificant concentration of stress near to foundation and at lower and upper slope both with infinite boundary (Figure 13c). This shows that building on face of slope is more stable with this boundary under dynamic loading. This shows the efficacy of the boundaries in earthquake persistent area. The boundaries of present study have sufficiently reduced the stress concentration and the SSI must be subjected to the slope-building interaction. It validates the study of building behavior on hill slopes[11,34,35] and the effect of boundaries on nuclear reactor building also[23]. Therefore, it is recommended that these boundaries should be implemented at various geomechanical and geotechnical problems[22].

Effect of PGA on slope-building: The impact of PGA on slope-building under SSI has been assessed as shown in table 4. This is one of the fundamental analysis for the structure treated under SSI. The amount of PGA required to trigger the failure in the slope-building system under SSI can be predicted. The present study shows the maximum displacement response for the nodes on the top of the building. The PGA values have been magnified from 0.13g to 1g and responses have been obtained under various boundaries.

The infinite boundary shows almost 50 % reduction in response than viscous boundary. The variability in maximum displacement for top node of building was observed for high slopes (slope 1:1). This slope was observed more susceptible to failure under varying PGA. Similar behavior was observed in recent studies of building behavior on slope[9,23,34,35].

Discussion

The hills are one which are most vulnerable in seismic excitation due to slope and human desire to construct the heavy structures like tunnels, bridges, high rise multi-storeyed buildings etc. These structures must be analysed with slope-building characteristics. Recently, many high rise buildings observed collapse in hills when subjected to seismic excitation.



(a) (b) (c)

Figure 13: Impact of boundaries (a) VB, (b) KB and (c) IB on slopes

Table 4
Maximum response at TOS

Boundary conditions →	VB			KB			IB		
Rise of Buildings → PGA↓	Low	Mid	High	Low	Mid	High	Low	Mid	High
				Slope1:1					
0.13g	57	65	72	39	48	56	24	29	32
0.25g	72	79	85	46	56	61	34	47	60
0.5g	105	118	128	100	110	119	65	77	90
1g	112	125	135	102	115	123	91	103	113
Slope 1:1.3									
0.13g	37	42	49	29	22	33	21	23	27
0.25g	49	60	64	34	42	51	30	44	49
0.5g	96	103	112	47	53	65	35	60	51
1g	104	121	128	94	101	113	49	76	91
Slope 1:1.6									
0.13g	16	21	33	11	16	21	7	11	14
0.25g	28	33	45	16	24	39	10	15	20
0.5g	50	63	77	27	33	48	18	23	32
1g	88	94	103	55	62	81	32	38	41

A numerical study was performed on combination of buildings on different inclinations of slopes considering SSI. Suitable buildings on slope have been evaluated under the effect of viscous boundary and results were compared with two more transmitting boundaries to observe the amplification factor, displacement and acceleration response and PGA effect on the buildings. The current boundaries showed the significant effect in the slope-building system. The consideration of SSI was observed effective in wave propagation problem in which soil is characterized by fixity condition of foundation. Energy dissipation mechanism showed that height of building in hills is characterised by slopes.

Again, PGA amplification response for free slope was analysed with seismic loading and it was found that amplification along the height of slope increases. The changes were observed and reported as 9 times at toe and 20 times at top node of building. It means that there may be a failure at top of slope. The relative change in PGA amplification was found on account of with and without structure under SSI effect. The observed PGA amplification factors in hilly regions have significant implications for both slope stability and building design. They emphasize the need for thorough geological and seismic hazard assessments, site-specific engineering solutions and appropriate regulations to mitigate seismic risks and ensure the safety of both the built environment and its occupants in these regions.

The slope stability parameters used in the study were further analyzed with boundary conditions and it was found that IB boundary is more beneficial in seismic design model. The study is limited to dry condition of soil, this aspect may be extended for saturation limit of soil. The current study recommends that the slope and buildings in hill are unstable due to height of building, amplification and proper boundaries conditions under seismic loading. These two are most important characteristics for construction on hills. The researchers and engineers may analyze first the building and slope with these criterion to implicate the design of buildings in slopes.

The present study is limited to dry soil slope condition. However, the wet condition and pore pressure may be considered for the precarious loading on slope and building on slope system.

Conclusion

The seismic stability of slope and building on face of slope has been studied to characterise the slopes. The three different buildings on face of slope with three boundary conditions have been analysed under seismic loading considering the SSI. The results of numerical investigation on SSB model analysis using FE method are presented.

1. The different heights of buildings on slope face have been simulated under numerical investigation and it was found that building on slope topography affects the behavior of buildings. It is recommended that SSI is needed in slope-building at design stage.
2. The effect of SSI was performed with flexible and fixed base. The free vibration was only observed 25 % with fixed base condition. This was 3 times larger than in case of flexible base condition. This obtained results recommend that the SSI must be considered for such kind of analysis in the geotechnical problems.
3. The toe of slope was found with initial propagation of stresses and shearing damage in the slope mass.

However, the crest and mid of slope were observed with amplification. It is recommended that these critical locations as crest, mid of slope and toe may be taken in account for the slope-building analysis.
4. The impact of SSI was obtained at the various locations of slope-building. It was observed that there is a significant increase in responses from more than 50 % at toe and crest of slope respectively.
5. The importance of boundaries in the analysis confirmed that PGA, acceleration and displacement response, shearing damage and stress accumulation change the behavior of building on slopes significantly.
6. The infinite boundary was observed with significant reduction in response of amplified PGA and structure loads. This leads to reduction in amplification response with slope angle and it was found more than 30 % and 40 % for 1:1.6 slope and 1:1 slopes respectively. Further, infinite boundary was able to reduce responses for all slope inclination considered significantly.

The conclusions of study may be applied to the underground structures like tunnels, heavy structures on slope and few other boundary value and wave propagation problems. Impact of seismic excitation on the stability of structures which will be built on this type of wet slopes, will alter the behavior of building and soil. Also, the slope stability under combined effect of strain localization due to past excitation and current seismic excitation can be studied for real behavior of geostructures.

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(Received 01st January 2024, accepted 03rd February 2024)