


Review Article

Strong Far-Field Vertical Excitation and Building Damage: A Systematic Review and Future Avenues

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Received 21 May 2020; Revised 14 July 2020; Accepted 20 March 2021; Published 30 March 2021

Academic Editor: Jian Ji

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Strong vertical excitation may lead to detrimental consequences on structures and infrastructures. To date, the impacts of strong vertical shaking on structures and infrastructures are considered for near-field regions only. However, anomalies in terms of recorded evidence and damage occurrence in the central Himalayan earthquakes dragged the attention of the researchers to explore the possibility of strong vertical shaking in far-field regions as well. Systematic review approach is used to sum up the findings from scholastic works reported to date and juxtaposed the findings with the evidence from central Himalayan earthquakes. It is concluded that the strong vertical shaking in the far-field is undeniable, at least in the central Himalayas; thus, incorporation of strong far-field vertical shaking in structural analysis and design is required. This paper reports the evidence reported in the literature for strong vertical shaking and adds evidence from Nepal focusing on strong far-field vertical excitation.

1. Introduction

With an increasing availability of accelerometric records, experimental and numerical studies on the effects of strong vertical excitations are appearing more frequently nowadays. Although moderate to strong earthquakes rarely occur and instrumentation is not adequate across the active seismic regions, the impacts of vertical excitations were surfaced mainly after 1990s. For many years, vertical shaking is considered to be significant in the near-field regions only. Possibly, due to the fact that the effects would be detrimental in the near-field regions, consideration of vertical excitation in near-field regions deemed necessary. Many researchers conducted analyses on the seismic behavior of several types of structures considering the near-field strong motion records (e.g., [1–6], among others). In high-frequency scenario, the vertical-to-horizontal spectral ratio would be greater than 2/3, which is commonly considered [7], even for source to site distance up to 40 km [8]. Meanwhile, the V/H

ratio would be smaller than 2/3 for a long period as reported by several researchers (see, e.g., [9–11], among others). Several earthquakes worldwide depict that strong vertical shaking in the near-field would be detrimental in terms of structure and infrastructure damage [12–16]. As all the historical evidences coincide with the fact that the strong vertical shaking is prevalent in near-field regions, experimental as well as numerical studies on the effect of vertical excitation on structures and infrastructures are also limited to near-field regions. To the best of authors' knowledge, the far-field strong vertical shaking has not gotten adequate attention although there are some remarkable shreds of evidence to support this aspect. To this end, systematic review was conducted on the effect of strong vertical shaking on buildings to shed light on the necessity of strong far-field shaking pertaining to the recorded and descriptive evidence of the occurrence of strong or strongest vertical excitation in the far-field. This paper aims to report the effect of vertical excitation through extensive literature review and to propose

a new dimension of the promising research field in the future.

2. Methodology

The systematic review approach is used in this study to identify and synthesize the findings of published works that emerged in the past decades. Further details regarding the systematic review approach could be found elsewhere (see, e.g., [17]). The schematic diagram of the systematic review approach is shown in Figure 1. The first step involves the formulation of the pertinent research question(s). In this study, research questions were postulated as follows: is strong vertical excitation significant in far-field too? Thereafter, we explored repositories such as Scopus, Mendeley, ScienceDirect, ASCE Library, Taylor and Francis Online, Wiley Online, Springer, Sage, ResearchGate, and Google. The keywords such as “vertical shaking,” “vertical excitation,” “far-field motion,” “near-field motion,” “structure damage,” and “building damage” among others were used to identify the potential works for literature review. Apart from the scholastic works, relevant codes and research works related to data and evidence for strong vertical shaking in near field were collected. In total 211 documents were prepared for initial assessment. Thereafter, initial screening was performed considering the quality of publication and publishers, indexation, duplication, and novelty of the works. After a thorough quality assessment, 118 documents from indexed journals, codes, data papers, reviewed reports, and reputed conferences papers were segregated. The papers from indexed journals, reviewed reports, and reputed conferences were used to perform an exhaustive literature review. It should be noted that our scope is limited to building damage due to strong vertical shaking; thus, infrastructure damages are not duly accounted. Thus, seismological aspects of strong vertical shaking and studies related to the effects of vertical shaking on bridges are not reported exhaustively, rather recognized only. The papers selected for review were screened to check the research alignment per our objective, and synopsis of findings from each reviewed content is presented. Critiques on existing studies are then delineated, and future insights and conclusions are formulated attributing the recent observations on far-field vertical shaking. The central Himalayan earthquakes were considered as the evidence to extend state-of-the-art practice to a new direction.

3. Effects of Vertical Shaking on Structures

One of the pioneering contributions in the effect of vertical shaking was made by Papazoglou and Elnashai in 1996 [18]. They critically analyzed the damages caused by the Kalamata, Greece, earthquake (1986) for the near-field damage analysis. They further noted that the historical earthquakes such as Skopje (1963), Managua (1972), Thessaloniki (1978), El-Asnam (1980), San Salvador (1986), and Spitak (1989) reflected the possibility of strong vertical shaking in the near-field regions. The Kalamata earthquake showed the V/H ratio up to 1.26 (for details, see [19, 20]) as reported by

[18]. Due to strong vertical shaking, the horizontal displacement of items had occurred without visible evidence of friction at the interface. Papazoglou and Elnashai [18] also presented field evidence of horizontally cracked reinforced concrete (RC) pedestal at midheight due to possible tensile action. Reports presented by several researchers (e.g., [20–24]) outlined the unusually high number of symmetric compression and shear-compression failures in columns and shear walls even in soft-story buildings. This evidence was not per the general expectation of the occurrence of bending failure; thus, researchers noted that strong vertical shaking would have been responsible for anomalous damage mechanisms. The soft-story construction is considered to have vulnerability concentrated to ground story, and occurrence of damage is generally expected due to formation of plastic hinges. The soft-story damage, strengthening, and seismic performance aspects are reported elsewhere (see, e.g., [25, 26]). Papazoglou and Elnashai [18] concluded that the discrepancy of vertical force was responsible for the reduction in shear strength due to loss/reduction of concrete contribution. Papazoglou and Elnashai [18] also presented the evidence of the 1994 Northridge and 1995 Hyogo Ken Nanbu earthquakes citing evidence of unusually strong vertical shaking and damage occurrence in modern buildings.

Several analytical investigations considering the effects of vertical shaking on buildings confirmed that varieties of buildings observe the same level of dynamic amplification due to vertical shaking as reported by Papazoglou and Elnashai [18] and analytical evidence presented by Georgantzis [27], Papadopoulou [28], Papaleontiou and Roesset [29], and Fardis [30]. The analysis conducted by Papadopoulou [28] highlighted that moment-resisting reinforced concrete (RC) frames show the variation of the vertical-to-horizontal fundamental period between 7 and 2.5 for 8- to 1-storied buildings. The analysis performed by Georgantzis [27] suggested that the behavior modification factor would be reduced by up to 30% when considering vertical excitation even though the V/H ratio is constrained to $2/3$ [31, 32]. Thus, consideration of vertical motion would result in the failure of the upper story(s). Papazoglou and Elnashai [18] concluded that column shear failure would be the governing factor for the ultimate response when the vertical component is included in analyses. Analysis of steel frame building by Broderick et al. [33] showed that the inclusion of vertical shaking did not affect the interstory drift; however, a 12% increase in column rotation ductility demand was prevalent due to the occurrence of lower yield rotation. The beam would be the most affected due to vertical shaking. In 1996, Papazoglou and Elnashai [18] shed light on the necessity of inclusion of vertical excitation in earthquake-resistant designs and analyses. However, a broad literature review reflected that the topic is still vital to be explored even after 25 years. Elnashai and Papazoglou [34] presented a method to assess the behavior of RC buildings subject to vertical shaking deploying piecewise linear relationship. They derived bilinear and inelastic spectra and concluded that the net tensile forces and displacement may lead to the reduction in the shear resistance of RC columns. They proposed a modal

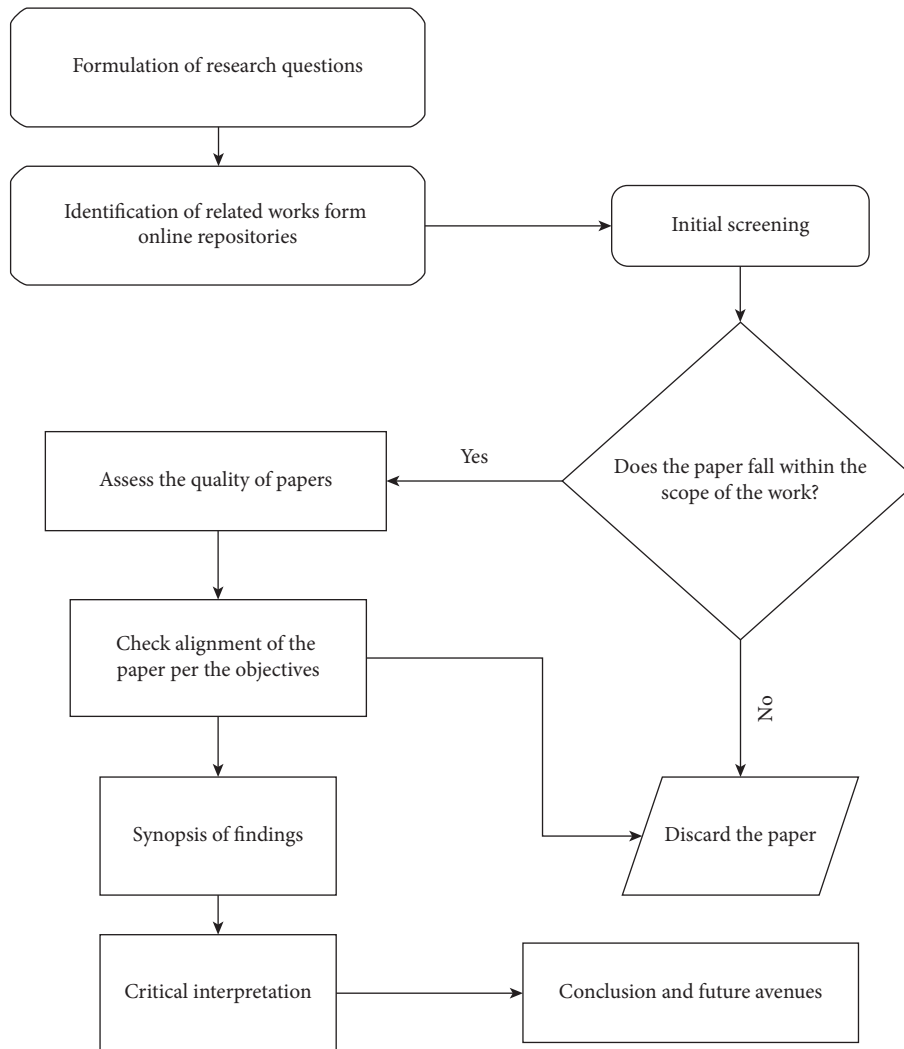


FIGURE 1: Systematic review approach implemented in the study.

analysis approach that could be deployed to estimate the vertical shaking forces. Their analysis highlighted that vertical excitation could lead to compression failure despite the safety factor for the fundamental load be in the range of 2.5. Ghobarah and Elnashai [35] presented the analysis in the contribution of vertical shaking on the seismic behavior of RC building considering low- and medium-rise RC buildings. They concluded that the vertical excitation would significantly affect the seismic performance of RC buildings. The vertical excitation was responsible for damage of existing nonductile RC moment-resisting frame building as well as the well designed RC building. The effect on drift was not severe when P- Δ effects become dominant. They further highlighted that 10–20% additional strength loss was attributed to the effects of vertical excitation. Similarly, the response modification factor was decreased by 30% when vertical excitation was accounted for. They reiterated that the near-field vertical shaking would lead to significant damage to the RC buildings.

In 2000, Diotallevi and Landi [36] presented an analysis of the vertical excitation in seismic response of a five-storied

RC frame building using several strong motion records. They compared the response of building with and without the vertical excitation and concluded that the vertical shaking would be detrimental due to the adverse effects in column behavior. They further presented that the vertical excitation would lead to considerable fluctuations in the axial force, and hence the column behavior would be anomalous leading to a significant variation in global structural response. A greater roof displacement was prevalent, and the number of plasticized regions was greater in the columns. Significant reduction in the ductility was responsible for high axial compression, and the moment-curvature loops had become more random, and the greater axial force was responsible for greater peak values of moment and shear. Elgamal and He [8] denoted that the V/H response spectra would be strongly dependent on period and source to site distance and further concluded that the commonly used V/H ratio of 2/3 would be too conservative at high frequencies for up to 40 km source to site distance. They concluded that significantly high frequency (≥ 8 Hz) was prevalent in vertical excitations. However, their review

and analysis are more focused on seismological aspects rather than impacts of strong vertical shaking on buildings. Similar seismological studies regarding the strong vertical shaking in near-field regions are also performed by several researchers (see, e.g., [37–44]). Mazza and Vulcano [45] performed analysis on the effects of combined vertical and horizontal components of near-fault ground motions in the nonlinear dynamic response of the base-isolated building. They concluded that the compressive force exceeded the corresponding load for balanced failure in all the stories except the top. Loghman et al. [46] assessed the performance of base-isolated structures mounted on a triple concave friction pendulum (TCFP) bearing deploying the vertical excitation and concluded that the maximum error in calculating the base shear of structure would be 29.5%. They pointed out that if vertical excitation is not considered for superstructure with <0.6 sec period, the base shear would be underestimated. They further remarked that the inclusion of the vertical component is also critical in practical designs. Dana et al. [47] presented a comparative study considering code-based pseudo-static vertical excitation and nonlinear response history analysis which considers vertical ground excitation for a whole steel frame building and several 2D steel frame buildings. They concluded that the conventional code-based approach would give rise to conservative results as this underestimates the interior column compression demands by up to 40% with an average of $\sim 20\%$. Similarly, the moments at the face of the columns were 65% greater than those for the code-based approach, and the magnitude difference was greater for upper stories when compared with the lower ones. Di Sarno et al. [48] performed finite element analysis of RC frame buildings using the recorded ground motions of the L'Aquila earthquake and concluded that the combination of horizontal and vertical ground motion is required for reliable seismic performance assessment. They highlighted the need for experimental and numerical assessment campaigns to rectify the mechanical models to evaluate the shear capacity of structural members. Mazza and Vulcano [49] and Mazza [50] depicted that the base isolators would sustain tensile loads under vertical excitation of the near-field earthquake. The consequence of such tensile loads may lead to the failure of the base isolation system due to large displacement. Recognizing the role of vertical seismic excitation in the modification of the axial stresses in masonry, Rinaldin et al. [51] performed nonlinear analyses of masonry structures to depict the lateral load resistance of masonry piers. They concluded that the inclusion of the vertical component may lead to an increase in demand/capacity ratio by an average value of 15% for the masonry piers. Liberatore et al. [52] performed the finite discrete element model of a masonry structure using recorded accelerograms. They concluded that vertical excitation induces more intense failures in masonry structures with small cohesion due to high-frequency content of the vertical shaking compared with the horizontal one. Elhifnawy et al. [53] considered four analysis schemes, viz., one horizontal component, two horizontal components, one horizontal and the vertical components, and two horizontal and the vertical components and found that the multiple components of the

earthquake significantly affect the axial forces and strain ductility factors of the columns. Meanwhile, the effect would not be considerable in terms of lateral deformation response. Abdollahiparsa et al. [54] analyzed the effects of vertical excitation considering soil-structure interaction in steel frame buildings. They concluded that the vertical excitation when combined with the soil-structure interaction effect may increase the axial force on columns by $\sim 50\%$, maximum vertical displacement on beams by twofold, and story drift by $\sim 40\%$. Asgarian et al. [55] performed nonlinear dynamic analysis of three moment-resisting frame buildings considering 15 recorded near-field accelerograms. They concluded that the vertical excitation does not significantly affect the dynamic response of the structure in the elastic range; however, they noted remarkable variation in the nonlinear range. Kim et al. [56] depicted that shear failure would be random when vertical excitation is considered in analyses. Wang et al. [57] obtained time histories of bending moment and shear capacities using numerical modeling and demonstrated that vertical excitation would affect both capacities due to high frequency and significant amplification leading to premature failure or anomalous failure modes and casted doubt in the use of capacity design approach. The shifting of brittle shear failure from ductile failure mode due to considerable variation in axial force and presence of tension in piers under near-field ground shaking was revealed by Hosseinzadeh [58] using numerical modeling and by Lee and Mosalam [59] using experimental approach.

As highlighted by Anderson and Bertero [60], seismic demand would increase in the case of coupling the horizontal and vertical components of strong ground motion due to increased lateral forces and $P-\Delta$ effects. Thus, many researchers felt the need for coupling the horizontal and vertical components of earthquakes to predict more realistic behavior. Ju et al. [61] proposed a methodology to perform three-dimensional dynamic analysis of buildings considering vertical excitation. They propose that four fundamental considerations such as division of the main girder into two elements, inclusion of secondary beams, avoidance of floor stiffness if the floor is too thick, and the use of 80% vertical effective mass led to precise results. With 1080 time-history analyses and 180 static analyses, they concluded that the relationships of extreme column axial forces and beam moments between vertical excitation and dead loads would be linearly proportional to the maximum acceleration taken from the response spectrum for the first vertical frequency. The method proposed by Collier and Elnashai [62] facilitates estimating the structural response under coupled vertical and horizontal components of strong ground motion. Gulerce and Abrahamson [63] and Gulerce et al. [64] developed and implemented the probabilistic seismic demand model and probabilistic seismic hazard assessment procedures to incorporate the randomness of strong ground motion and variation in structural characteristics. They also proposed that the ratio of vertical to horizontal motion would serve as the intensity measure for probabilistic seismic demand models. The study by Warn and Whittaker [65] highlighted that the direct sum of the peak axial forces

(vertical) that would be induced by the vertical excitation and overturning moment would overestimate the actual axial force on bearing. To this end, Wei et al. [66] highlighted that the simplified approaches may be effective in the estimation of seismic demands of structures but fail to incorporate the variation in moment capacity, shear capacity, and ductility related to the interactions of horizontal and vertical excitations. Recognition of vertical excitation led damages has also emerged after significant earthquakes as reported by Augenti and Parisi [67], Gautam and Chaulagain [68], Kim and Elnashai [69], Bovo et al. [70], Nadim et al. [71], and others. However, the majority of forensic interpretations and damage analyses lack explicit evidence regarding the effects of vertical shaking on structures. Meanwhile, Ambraseys and Simpson [11] and Kale and Akkar [72] have proposed vertical spectra for Europe. Ercolino et al. [73] performed forensic analysis and numerical modeling to assess the causes of roof damage during the Emilia-Romagna earthquake and justified that the collapse of roof elements was attributed to the vertical component of earthquake in the near-field region. Due to the occurrence of considerably large vertical excitation, high relative displacement and low frictional resistance were noted as uplift phenomena in nonlinear dynamic analysis considered by the authors. The effect of three components of earthquake excitation could be in particular more influential for low period structures with sliding support [74]. Similarly, Liauw et al. [75] highlighted that the vertical response of structure is the function of frictional stress that is governed by the supporting element on the foundation pad. They concluded that the inclusion of vertical excitation contributes in the sliding system. Similarly, Lin and Tadjbakhsh [76] confirmed that the vertical excitation can in particular affect the foundation system that is harmonically excited. The high-frequency content associated with the early period excitation due to vertical component of strong motion was reflected in several numerical studies (e.g., [51, 77–84]). Kim et al. [84] performed numerical studies of 13 RC buildings considering the effects of strong vertical shaking. With the variation of vertical-to-horizontal PGA ratio, they studied the effects on vertical excitation on axial force, shear capacity, and shear demand of RC columns. They finally concluded that the vertical excitation leads to the variation in axial force and shear capacity so that vertical excitation cannot be left behind for the purpose of seismic assessment and design of RC buildings. Tian et al. [83] concluded that the effect of vertical ground shaking will not be significant when considering interstory drift as a performance parameter; however, punching failure will dominantly occur, which is seldom expected in horizontal excitations only. They highlighted that the punching failure will reduce the lateral drift capacity by 23%. Lu et al. [85] conducted shake table testing of suspended ceilings. They observed the occurrence of damage to suspended ceilings due to both horizontal and vertical excitations. The experimental campaign concluded that damage to suspended ceilings is not governed by the horizontal shaking. On the contrary, the vertical shaking significantly contributed to the failure of the suspended ceiling-frame system [85]. Hosseini and

Nezamabadi [86] studied the vertical response of Iranian steel buildings considering three-, four-, and five-storied steel buildings. Scenario analyses performed considering the vertical excitation and without considering it resulted considerable variation in compression and tension leading to noticeable uplift. They further justified that the effects of vertical shaking will be more pronounced in moment frames rather than the bracing members. The authors numerically validated that the effect of vertical component will be more concentrated in the upper stories rather the lower ones. Furthermore, the base shear ratio estimated for linear to nonlinear analysis scheme was obtained in between 0.34 and 1.89 [86]. Yamazaki et al. [87] also studied the effects of vertical excitations on steel frame constructions. They concluded that the fluctuation of axial force in weak columns is more significant than the same in weak beams. The numerical and experimental analyses highlighted that the ratio of vertical to horizontal fundamental vibration period was 0.2 or less [87]. Their analysis also highlighted that the vertical excitation would affect the interstory drift in the range of $\pm 3\%$, which indicates that the horizontal excitation dominates the lateral displacement significantly than the vertical one. The authors concluded that the increase in axial force will give rise to significant reduction in shear capacity and thus aggravate the possibility of shear failure. Guo et al. [88] studied the combined effect of horizontal and vertical ground shaking on RC chimneys using fragility based assessment. They considered near-field ground motions to assess the seismic behavior and constructed fragility functions. They concluded that the likelihood of failure will be significantly increased when horizontal component of ground shaking intensity is significantly large. They recommend the use of combined horizontal and vertical excitations in seismic vulnerability assessment of RC chimneys. Similarly, Nezamabadi et al. [89] assessed performance of regular and mass asymmetric structures. They outlined that the near-fault vertical shaking will have significance, and thus the vertical design spectrum can be used to incorporate the effects arising from strong vertical shaking in near-fault regions. Furukawa et al. [90] conducted full scale shake table testing to assess the seismic response of base-isolated structure considering vertical excitation. The analysis performed by [91] showed that the displacements will be increased by up to 56% in a three-storied steel building when considering the vertical component of ground shaking. However, they used near-fault strike-normal strong ground motions only. They also noted that the vertical shaking will increase axial forces in column.

Several other studies perform analysis of building systems with base isolation to quantify the effects of vertical excitation (e.g., [49, 74, 92–95], among others). From the above discussions and broad literature review, it should be noted that the necessity of consideration of vertical excitation in design and code formulation is a must to capture the anomalous behavior of buildings during earthquakes. Furthermore, it is clear that the strong vertical shaking in the global context is confined to the near-field regions only. As limited studies have duly focused on the impacts of vertical shaking and have reiterated the need for formulation of

TABLE 1: Summary of strong motion records after some Himalayan earthquakes (modified from [113–115]).

Accelerometric station	Earthquake	Epicentral distance (km)	Recorded PGA (g)			V/H
			EW	NS	UD	
NSC	Gorkha (2015)	80	0.13	0.18	0.2	1.27
Kantipath	Gorkha (2015)	81	0.13	0.14	0.17	1.26
Kirtipur	Gorkha (2015)	80	0.25	0.15	0.12	0.58
Tribhuvan University	Gorkha (2015)	81	0.22	0.16	0.14	0.73
Patan	Gorkha (2015)	83	0.13	0.15	0.13	0.93
Thimi	Gorkha (2015)	87	0.12	0.15	0.18	1.33
NSC	Nepal-Sikkim border (2011)	272	0.032	0.05	0.018	0.43
Gangtok	Nepal-Sikkim border (2011)	70	0.15	0.16	0.13	0.84
Siliguri	Nepal-Sikkim border (2011)	115	0.16	0.2	0.12	0.66

vertical spectra for analysis, no significant improvements could be found in the existing literature regarding this regard. Although the scope of the paper is limited to building structures only, the authors recognize the notable contributions in the field of bridge engineering considering the effects of vertical excitation as reported elsewhere (see, e.g., [66, 96–101], among others). Despite buildings and bridges, many researchers have considered the vertical excitation to assess the seismic performance of various types of structures (e.g., [88, 102–106], among others).

4. Evidence and Avenues beyond Near-Field Regions

Virtually all existing literatures report the strong vertical shaking during an earthquake in the near-field region only. On the contrary, the focus of this paper is to drag the attention of the researchers towards strong vertical shaking in the far-field region. Studies by Collier and Elnashai [62], Ambraseys and Simpson [11], Ambraseys and Douglas [107], Kalkan and Gulkan [108], Gulerce and Abrahamson [63], and Boomer et al. [109] highlighted that the vertical to horizontal spectral ratio is the function of source to site distance as well as local soil condition. Accordingly, the Kathmandu Valley as well as other valleys that are located in the alluvial deposit may observe significant local site effects during earthquakes (see, e.g., [43]). In this case, vertical excitation would be dominant and may result in anomalous damage mechanisms. The first evidence of strong vertical shaking and associated damage in Nepal was reported by Rana in 1935 [110]. In the monograph, the author reported that despite being ~150 km away from the epicenter of the 1934 earthquake [111], buildings in Kathmandu Valley observed damage to the upper stories and also noted that the shaking was up down due to strong vertical shaking. Ground motion records in Nepal are available for 2011 and 2015 earthquakes only, so the account by Rana [110] cannot be numerically justified. Table 1 summarizes the peaks of horizontal and vertical components of recorded earthquakes in central Himalaya together with the epicentral distances and V/H ratios. As shown in Table 1, the 2011 earthquake was recorded at 70, 115, and 272 km from the epicenter. Notably, even the recording at 70 km shows V/H ratio as 0.84. Similarly, at 115 km, the ratio appears to be 0.66, and at 272 km from the epicenter (at Kathmandu), the ratio is still

0.43. Although significant damage did not occur in the instrumented location in Kathmandu Valley during the 2011 Sikkim-Nepal border earthquake, however, clear evidence of strong vertical shaking in the far-field was present. In 2015, Nepal was struck by a strong earthquake of moment magnitude 7.8. Several instrumental recordings are also available for the earthquake. As shown in Table 1, all except one recording in Kathmandu valley, which is more than 75 km far from the epicenter, depicted the V/H ratio more than 2/3 (Figure 2). At 80 km epicentral distance, the ratio is obtained as 1.33. The range of V/H in Kathmandu Valley is obtained between 0.58 and 1.33. This signifies that the central Himalayan earthquakes are likely to depict strong if not strongest vertical shaking even in the far-field regions. Figure 3 depicts that the frequency of vertical shaking was ~10 Hz which should have played a vital role in anomalous building damage as reported by Gautam et al. [111]. The accelerometric station is located on loose soil deposit area so there is also a possibility of seismic site effects. The Kathmandu basin is ~500 m deep, and interbedding of silts, sands, and clay is dominant [112]. This could be one of the possible reasons behind the strongest vertical shaking in central Kathmandu during the 1934 and 2015 earthquakes.

As opposed to the world earthquakes, as reported by Broderick et al. [33] and Elnashai et al. [116], the central Himalayan earthquakes depict relatively similar or greater V/H ratio even in the far-field regions when compared with the near-field records of Northridge and Kobe earthquakes. Apart from seismological evidence, the 2015 Gorkha earthquake in Nepal displayed exemplary evidence regarding the effects of strong vertical excitation in far-field. Figure 4 shows a soft-story building with a collapsed third story due to strong vertical shaking which is similar to the evidence presented by other researchers in the near-field regions. The excessive axial force due to vertical excitation that usually becomes more significant in upper stories should have caused the collapse. Except for the collapsed story, the building sustained minimal damage. Several cases of upper story collapse were reported in Kathmandu Valley, especially in the soft soil deposit locations. The V/H ratio also depicts the higher value especially in the case of soft soil locations such as Thimi and NSC (Table 1). Similarly, shear damage in the columns in the seventh story of a 14-storied apartment building was prevalent in the downtown of Kathmandu. It is pertinent to note that shear damage to

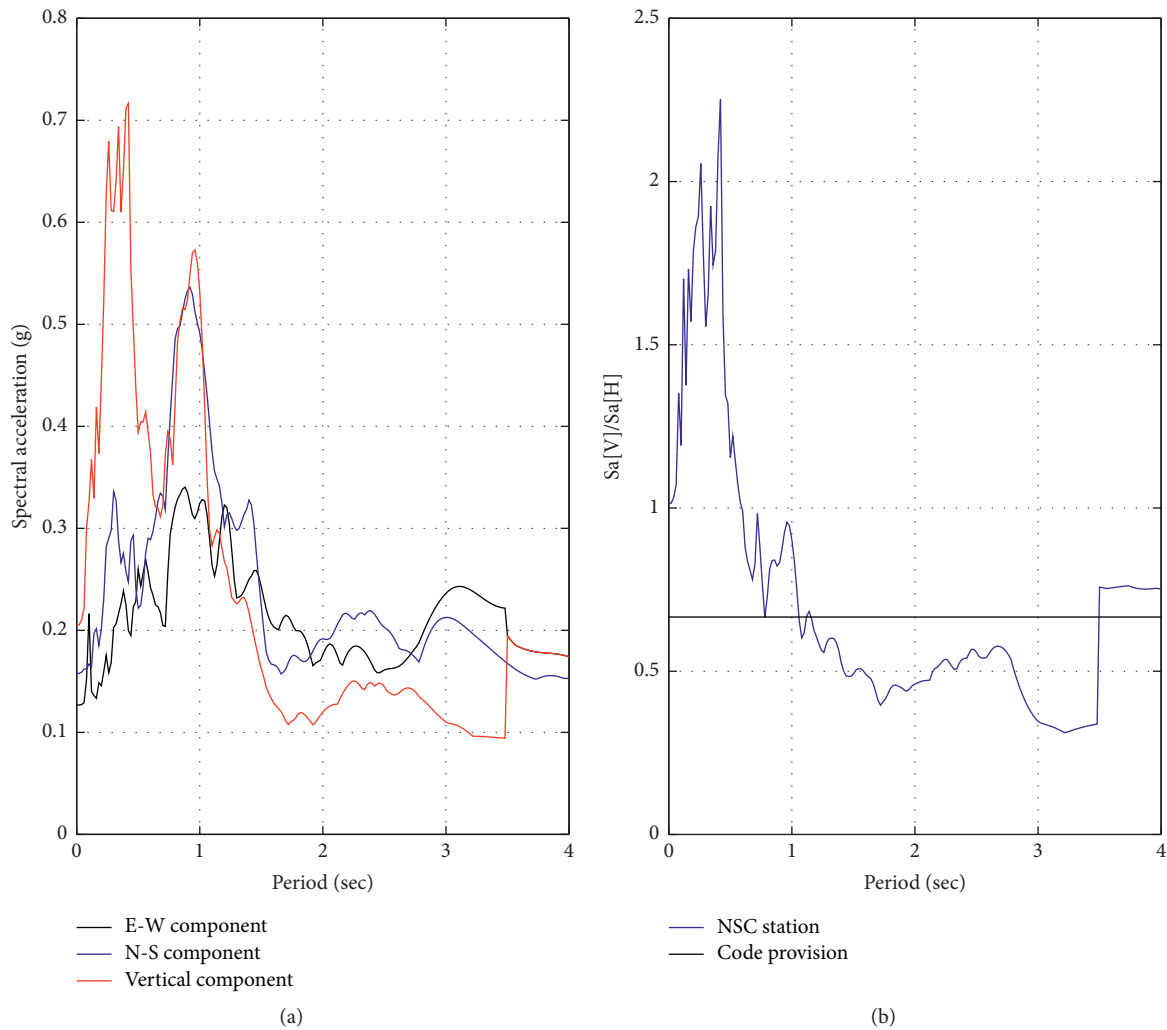


FIGURE 2: (a) Acceleration response spectra of the 2015 Gorkha earthquake recorded by National Seismological Center (NSC) [117] and (b) vertical to horizontal spectral ratio for the Gorkha earthquake.

columns in the location where maximum shear force is not expected (Figure 5), intermediate/upper story collapse (Figure 6), and shear-compression failure of internal columns among others clearly indicate the presence of strong vertical excitation during the Gorkha earthquake in the far-field regions. These shreds of evidence strongly demand due consideration of vertical excitation during seismic code formulation. The Nepal Building Code [31], on the contrary, does not account for the effects of the vertical shaking on building except for secondary structural elements. However, the earthquakes that struck Nepal Himalaya have consistently notified that the strong vertical shaking in far-field is significant. So, further research is needed to quantify the effects of strong far-field shaking beyond the conventional near-field analyses. To quantify the effects of strong far-field excitation, numerical studies and parametric analyses are required. We aim to perform studies based on finite element analysis considering strong far-field excitations considering parametric analyses. Furthermore, the effect of soil-

structure interaction in the case of far-field vertical excitation will be more influential in terms of foundation performance. So, studies that consider the effect of soil-structure interaction together with strong far-field vertical shaking are also important to capture the anomalous behaviors of buildings that were observed during several historical earthquakes. In the case of strong far-field excitation, the conventional design guidelines may not assure adequate seismic performance as shear damage in the middle portion of columns, higher axial force demand in the upper story column, and others could lead to unprecedented mechanisms and damages. Thus, experimental campaigns considering the effects of strong far-field vertical excitations will further advance the understanding regarding the mechanisms and possible remedial measures that could be implemented in building codes. To achieve the target performance of buildings in seismic areas, the occurrence and possible effects of strong far-field shaking should also be considered in contemporary seismic designs and assessments.

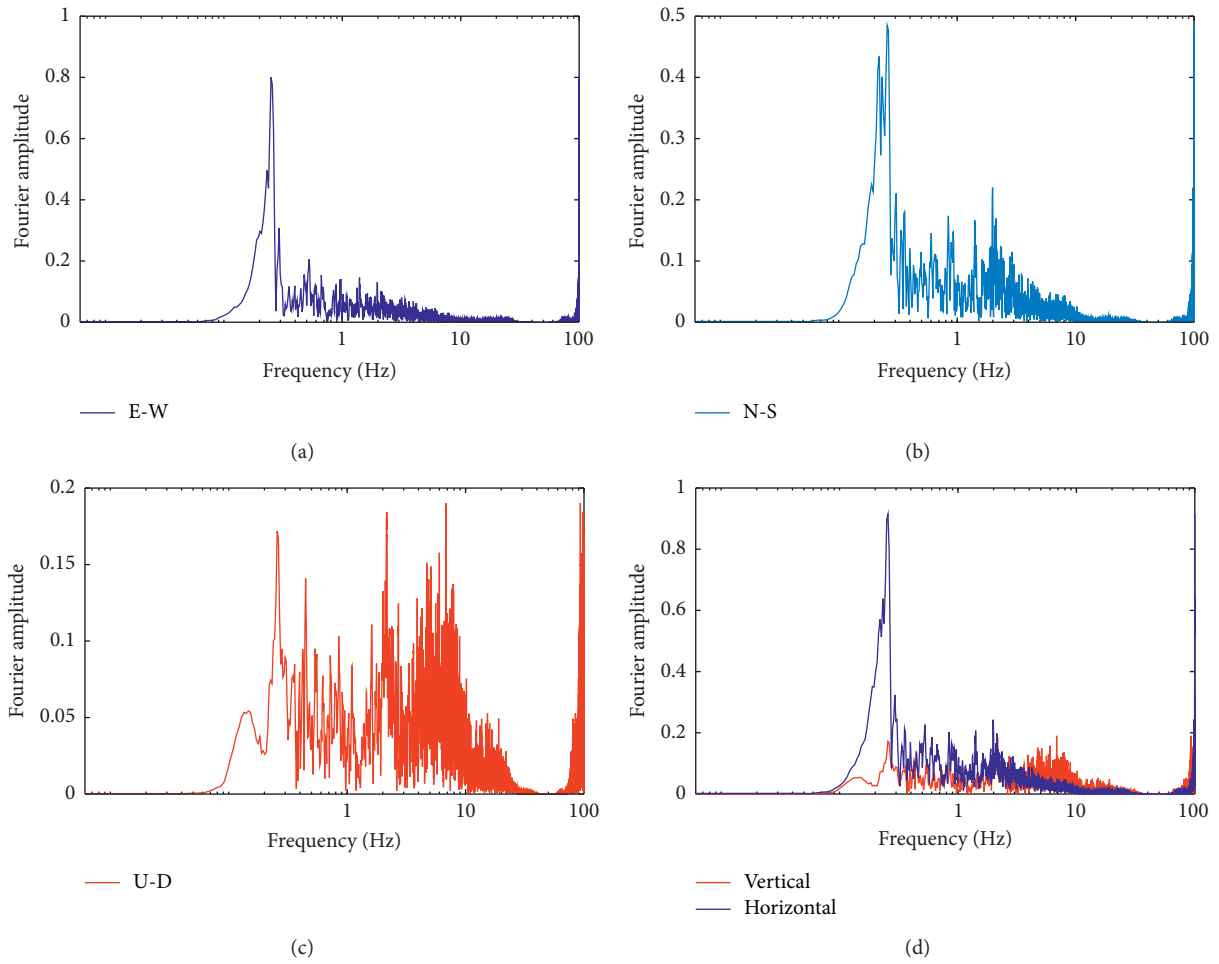


FIGURE 3: Fourier spectra of the Gorkha earthquake: (a) east-west (E-W) component, (b) north-south (N-S) component, (c) vertical (U-D) component, and (d) vertical and horizontal components.



FIGURE 4: Intermediate story collapse in a modern hotel building compliant to the prevalent code at Nagarkot, Bhaktapur, Nepal.



FIGURE 5: Shear damage of a column at midheight in Kathmandu due to the 2015 Gorkha earthquake.



FIGURE 6: Collapsed top story in a soft-story building in Kathmandu by the Gorkha earthquake.

5. Conclusion

A systematic review on the effect of vertical shaking on buildings is presented in this study. With the help of a broad literature review, the evidence for near-field and far-field vertical excitations is summarized. The sum of the reported

evidence highlights that there are anomalous damage mechanisms that could not be explained by the conventional analyses. This supports the significance of inclusion of strong vertical excitation in the far-field regions too. Numerical simulation results presented by several researchers also highlight the clear evidence of detrimental impacts on

structures at least in terms of greater axial forces in the upper stories, occurrence of shear damage in noncritical regions, damage to interior columns, and variation in base shear, among others. However, virtually all previous works focused on the near-field regions only; thus, the strong far-field vertical excitation has not gotten adequate attention so far. The evidence from central Himalayan earthquakes shows that the strong/strongest vertical shaking is not limited to the near-field regions only and that may also lead to detrimental impacts on structures in the far-field regions. The damage mechanisms in far-field regions due to recent earthquakes are presented together with the V/H ratios of accelerometric records. It is concluded that there is a dire need for investigation regarding the occurrence of strong vertical shaking in the far-field regions as well and its impacts on structures and infrastructures. Further numerical and experimental campaigns are required to address this scenario. In addition, seismic codes should also consider the impacts of strong far-field vertical excitations. This study reports only a few pieces of evidence of occurrence of strong vertical excitation in the far-field regions and the related damages. The authors would perform numerical analysis using strong far-field vertical excitation to assess the seismic performance of RC buildings. Moreover, future works may also consider experimental studies implementing strong far-field vertical excitations.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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