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State-of-the-art of Study on Seismic Behavior of Structures in Mountainous Terrain and Establishment of the Specification for Structural Design

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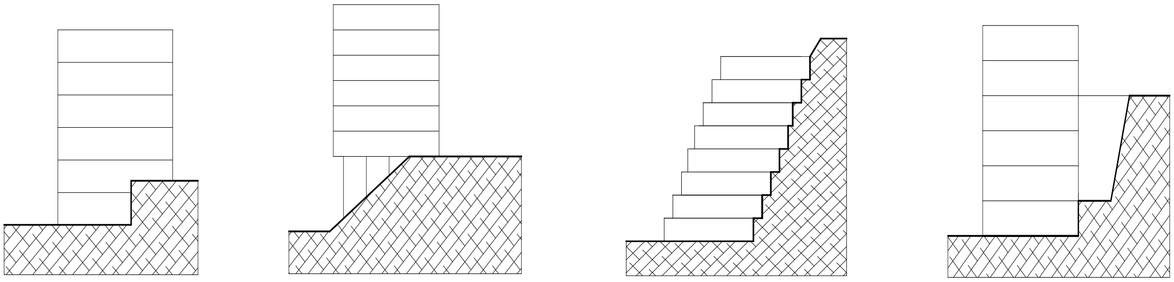
Abstract

The rational structure model, inputting load and seismic response of structures in mountainous terrain are different from those of common structure in structure analysis and structure design due to the particularity of site and foundations with two or more different elevations. Although extensive researches on structures in mountainous terrain have been conducted, there still exist some disputable and unknown issues on seismic design. The paper presents an overview of the progress in research regarding seismic behavior of structures in mountainous terrain and recommends the special specification for structural design. Three parts of the subject are stated. The first is the introduction of the special problems existing in seismic behavior and design of structures in mountainous terrain consisting of conceptual design, anti-seismic calculation and details of seismic design. The second part encompasses the studies and shortage of these special problems such as seismic motion input, rational structure model, seismic behavior, irregularity control of plane and elevation and analytical method. Lastly, the major framework and code clauses aiming at special problems are sketched.

Keywords: Structures in Mountainous Terrain; Specification for Structural Design; Seismic Behavior

1. Introduction

With the conflict between the expansion of cities and the lack of building site, and the acceptance of the idea of harmony between human and nature, structures in mountainous terrain coordinating with environment are constructed more and more [1, 2], which contain multistory buildings and high-rise buildings [3].Generally, structures in mountainous terrain refers to the structure whose embedding ends are placed in different elevations and can't be simplified to the same elevation in analytical model [4].The main difference between structures in mountainous terrain and common structures is whether the foundations are built on different elevations. Typical types of structures in mountainous terrain are shown in Fig. 1.



(a) (b) (c) (d)

Fig. 1 – Typical types of structures in mountainous terrain; (a)structure supported by foundations with different elevations; (b)stilted structure on the slope; (c)structure attached on the cliff; (d)structure connected with steep

In the early 1990s, Indian researchers began preliminary analysis of structures in mountainous terrain [5-8], while it didn't attract much attention at that time. In recent years, earthquake damage with varying degree to structures in mountainous terrain with foundations on different elevations emerged during WenChuan earthquake [9-10], Sikkim Earthquake [11] and Nepal earthquake, which gave rise to more attention and studies on the special problems and seismic behavior of structures in mountainous terrain. Extensive study results were obtained in aspects of stress and deformation performance, failure mechanism, seismic motion input, stability of slope and special members with complicated stress, etc. Regarding practical application in seismic design, research on rational structure model and control of irregularity had been proceed to some extent.

The special performance of the structures in mountainous terrain makes it inappropriate to apply the existing Chinese codes [12-13] to the design of this kind structure. On the basis of current research and practical engineering experience, the specification for seismic design of structures in mountainous terrain has been established as guidance.

2. Special Problems of Structures in mountainous Terrain

Earthquake damage investigations [9-11] indicated that the earthquake damage of structures in mountainous terrain was different from that of common structures, and in general, the former was more severe. Because of the special site, seismic input motion of structures in mountainous terrain is complicated. There are significant differences in dynamic property, stress and deformation characteristics between structures in mountainous terrain and common structures because of the former's innate structural irregularities in plane and in elevation. Moreover, the failure mechanism is complex. It's necessary to understand these special problems deeply.

Since the complex site and special stress and deformation characteristics, the special problems of structures in mountainous terrain exist in the process of analysis and seismic design.

To ensure structural safety and normal service, the stability of slope must be guaranteed. For structures in mountainous terrain, the slope within the scope of foundations makes local site condition complex, meanwhile, structure on the slope will affect the stability of slope and the effect should be considered during the analysis of stability.

Conceptual design is the general control to seismic behavior of overall structure. The total height limit, depth-width ratio and regularity limit are the criteria normally used to reflect conceptual design. Because of the complexity of embedding ends, there are two problems during the application of those criteria: the suitability and calculation method. These criteria are suggested to take account of studies on stress and deformation characteristics, economy conditions and a large amount of engineering practice and experience. Without special feature of structures in mountainous terrain considered, whether these indexes are suitable for structures in mountainous terrain needs to be checked. Design codes stipulate calculation methods and limit the value of total height, depth-width ratio and irregularity controlling index, while how to use those in structures in mountainous terrain remains to be discussed.

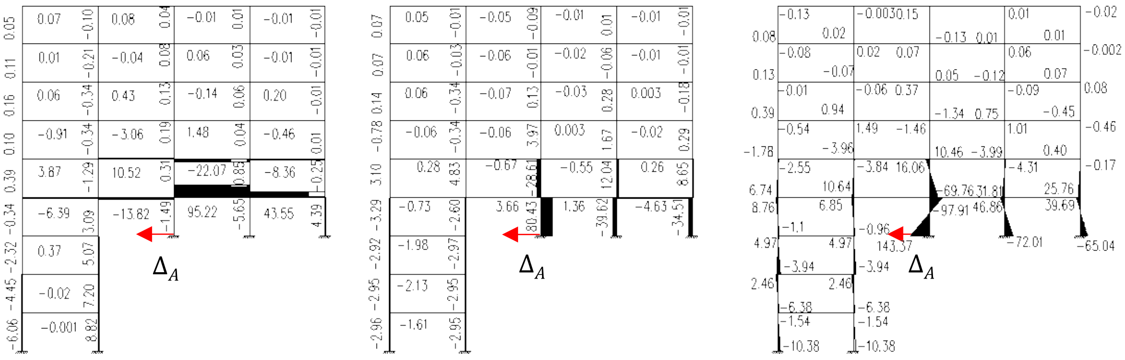
Rational seismic motion input and analytical model are preconditions for accurate analysis. The seismic input motion is complex for structures in mountainous terrain because of slope-structure dynamic interaction, which includes the amplification of waves, multi-support excitation of different heights embedding ends and dynamic soil pressure. Detailed model that contains the soil-structure interaction is the perfect analytical model of structures in mountainous terrain, while it is inconvenient to be applied to the design for its complexity. For simplified model, the method to simulate the soil property and embedding type concerns its rationality. It is worth taking account of the impact of slop on seismic motion input and analytical model.

Details of seismic design are the guarantee of seismic behavior. The special stress and deformation characteristics and failure mechanism result in specific components such as beams with considerable axial tension, columns with significant torsion. Some additional measures are needed in particular area.

3.Main relevant research work and results of Structures in mountainous Terrain

3.1 The stability of slope

N.Mizal-Azzmi et al. [14] researched geotechnical approaches for slope stabilization in residential area, and influence factors of slope stability were given. According to D.K. Paul and Satish Kumar's [15] study on the stability of hill slope with building loads, the failure of slope represents as either local failure under the column footing near the slope or overall failure of slope including the buildings. To check the stability of slope, the effect of building should be taken into consideration.



(a) (b) (c)

Fig. 2 Internal force of example structure with foundation deformation (Δ_A=1mm): (a) axial force (kN); (b) shear force (kN); (c) bending moment (kN.m)

On the other hand, uncoordinated base deformation among columns embedded on unequal heights may occur result from the deformation of slope, which will lead to internal force in structure located on slope. Liu and Luo [16-18] studied the mechanics behavior of structure supported by foundations with different elevations with imposed single displacement at upper embedding end, and the results indicated that the structure located on slope can generate relative greater internal forces even though tiny deformation happens in the slope (as shown in Fig. 2). This fact explains that ensuring little deformation of slope is preliminary condition for building structures in mountainous terrain, and how to guarantee the limited deformation of slope should be emphasized in practical engineering.

3.2 Seismic input motion

The impact of local terrain on ground motion studied by DAVID M. BOORE [19], suggesting that amplification effect of ground motions on structures resulting from local terrain should not be ignored. In Wenchuan earthquake, the buildings located at the top of slope and distributed between top and bottom of slope were more seriously damaged by earthquake than those situated in place featuring plain[9-10], indicating that both design factors and the amplification effect of ground motions should be placed equal role considering their contribution to damage of structures.

By simulating 2-Dimension terrain with respect to variations in slope angle and slope height, Wang and Ren [20-21] studied the influence of characteristics of terrain on response spectrum. The presented result was that the amplification coefficient of design ground motions was derived from the section of slope with rock layer, while this coefficient was cautiously applied into slope with soil layer.

There is another problem on how to reasonably consider the input of ground motions in different locations of embedding ends in consideration of seismic behavior of structures in mountainous terrain, namely, multi-point excitation. Through studying structures built on the soft soil, if employing model based on rigid foundation, it is necessary to take contrast of input ground motions between upper and lower embedding ends into consideration, when the height difference among embedding ends is huge [22]. However, there is no further study on how to consider this contrast of input of ground motions arising from different locations, currently. There is no relative study in terms of dynamic soil pressure, either.

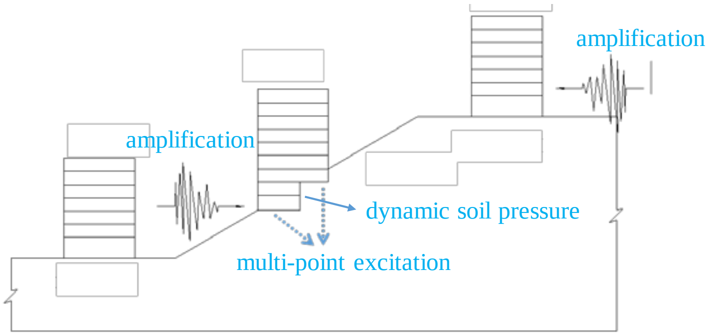
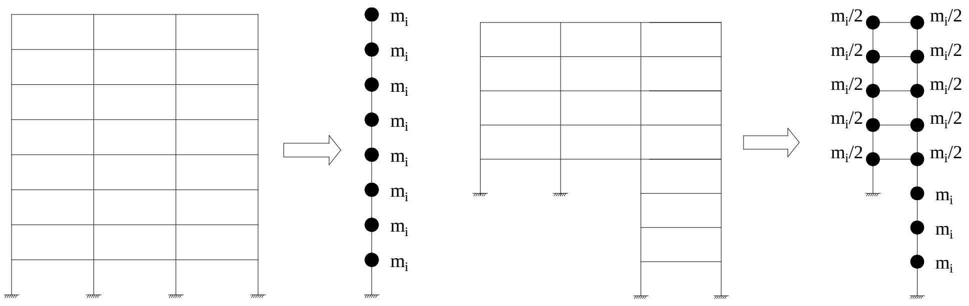


Fig. 3 – The problem of seismic input motion

3.3 Analytical model

The various kinds of simplification and approximate hypothesis applied into structural analysis should be supported by theoretical and experimental evidence or verified by engineering practice. The aspects of analytical model of structures in mountainous terrain including computational graphics, boundary conditions should be consistent with actual working condition of structures.



(a) (b)

Fig. 4 – Comparison of simplified analytical model; (a) common structure;(b) structure in mountainous terrain

For ordinary structures, simplified multi-degree of freedom and multiple mass points model, namely, equivalent mass-stiffness model, as shown in Fig. 4(a), is typically representative to study dynamic characteristics and stress and deformation characteristics; meanwhile, performance of structures with unequal height embedding ends also may be discussed based upon equivalent mass-stiffness model. The model is set up as presented in Fig. 4(b) [23], where m_i denotes total mass of i^{th} floor. While, this can cause deviations between analytical results and actual structures due to inevitable fact that the structure established on slope exists torsional deformation as featuring irregular distribution of stiffness and mass while the plane model does not reflect this, so this kind of structure pertinent to simplified model is necessary to be further studied.

In aspect of slope-structure interaction, the analysis results of multi-story frame with respect to slope-structure interaction by re-developing Ansys software indicated that seismic behavior of multi-story frame was prominently influenced by foundation [24].

The study [22, 25] of soft soil slope on seismic response of structure by detailed finite element model indicated that the distribution of shear force in grounded columns was effected and the participation degree of high mode increased as the property of soil was taken into account, and suggested that failure mechanism of structure differed from counterpart based upon hypothesis of rigid foundation. What's more, internal force and deformation of structure supported by foundations at different elevations were underestimated with respect to hypothesis of rigid foundation. Therefore, the simulation of the influence of slope concerns the accuration of analytical model, while the method of modeling irrespective of influence from foundation is common and it is necessary to further study on the situation where and how the influence of foundation should be considered.

3.4 Seismic behavior and failure mechanism

Recently, as an innovative type of structures, structures in mountainous terrain are gradually accepted by national specialists due to its distinctive performace by a serise of studies including structure supported by foundations with different elevations, stilted structure on the slope with respect to various kinds of factors and variations in parameters.

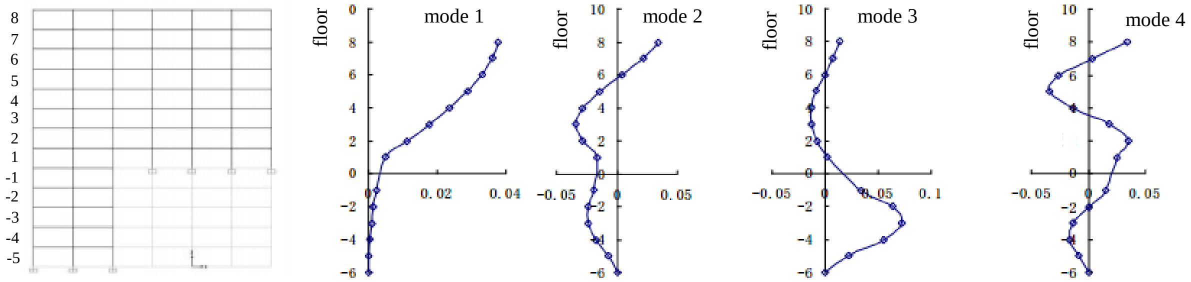
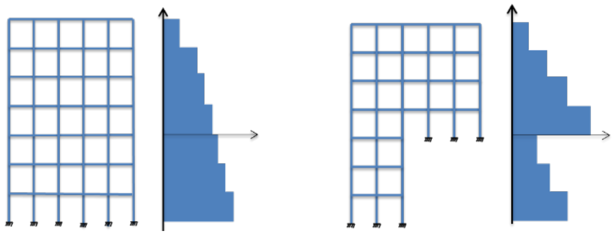


Fig. 5 Distributions of mode shapes

Based on comparison of dynamic performance for structures supported by foundations with different elevations in terms of different distribution of stiffness and mass [23], it was indicated that the modal participation factor of fundamental frequency increased as the increase of stiffness of floors under upper embedding end and the influence of high mode on response of structure should not be ignored at floors under the upper embedding end (as shown in Fig. 5). Furthermore, it was unsafe for floors under the upper embedding end to comply with codes [12-13]which requires at least 90% of cumulative modal mass participating coefficient. Compared to ordinary frame, the torsional effect of 3-Dimension frame structure supported by foundations with different elevations was comparatively remarkable [26-28]. B.G. Birajdar [29] compared dynamic response of three configurations of step-back building, step-back-set-back building and set-back building and suggested that step-back-set-back buildings were more suitable on sloping ground.

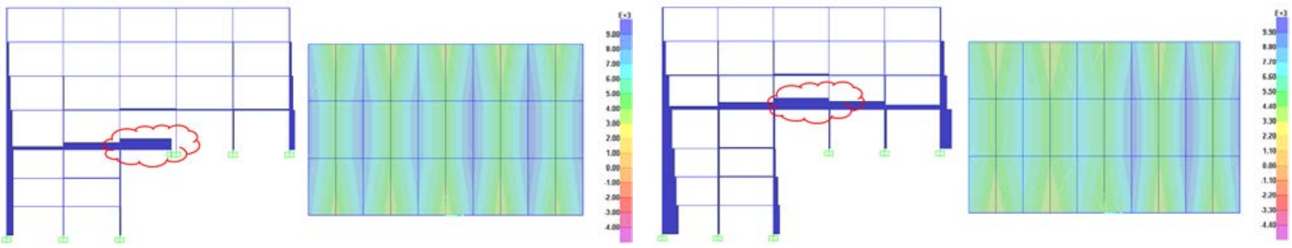
To compare the difference of stress and strain characteristic between frame structure supported by foundations with different elevations and common frame structure, Wang [30] studied these two kinds of structures applying response spectrum analysis, and results indicated that story drift angle and story shear of floors under the upper embedding end were far less than that in common frame, whereas, story drift angle and story shear of floors above upper embedding floor were slightly greater (see Fig. 6). Meanwhile, the maximum story shear was located at upper embedding floor rather than first floor and most of story shear was transferred to foundation through structural members located in upper embedding ground. Yang [31] proceeded preliminary research into dynamic performance of stilted frame structure on the slope with respect to displacement and distribution of shear. Results turned out that there was no obvious contrast between stilted frame structure on the slope and common frame except remarkable torsional effect. A.R. Vijaya Narayanan [11] proposed RC buildings with large plan configuration were vulnerable to strong seismic motion through comparison of seismic behavior among structures on the slope with varying embedding types and plan configurations. Y. Singh [32] examined the dynamic characteristics and seismic behavior of hill buildings via modal analysis, elastic time history analysis and elasto-plastic time history analysis, and presented that the story immediately above the road level was particularly vulnerable to earthquake action. These relevant investigations of mechanics characteristics reveals its dynamic characteristic and force-transferring mechanism to some extent.



(a) (b)

Fig. 6 Comparison of shear distribution a) shear distribution of common structure; b) shear distribution of structure in mountainous terrain

The effect of different patterns of support constrains on seismic performance was researched by Han and Tang [33-34]. It is discovered that the story drift and deformation were influenced by the constraint condition of column base of upper embedding floor. When sliding support was employed, the story drift of floors under the upper embedding end increased as bearing all story shear of upper embedding floor.



(a) (b)

Fig. 7 Sketch of axial force and stress distribution of upper embedding floor: (a) structure supported by foundations with different elevations with tensional beam; (b) structure supported by foundations with different elevations without tensional beam

Whether or not setting tensional beam influences the structures in mountainous terrain in terms of story drift, plastic energy dissipation and distribution of structural damage. Huang's study [35] suggested that without tensional beams, beams located between grounding and non-grounding columns of upper embedding floor beared comparatively great axial force, otherwise, the axial force of tensional beams were great. Also, for the slab of upper embedding floor, the stress distribution is different (Fig. 7). It should be noted that the occurrence of yield in columns on upper embedding end is prior to others regardless of whether or not the structure sets tensional beam.

The study on structures in mountainous terrain with shear wall is rare so far, and the mere research [36] is to analyze the impact of the number of floors under upper embedding end and location of shear wall on structural performance by examining mechanical characteristics and seismic behavior of frame-wall structures and tube structures. The concerned problem that the distribution of shear forces in shear walls and frame columns and the estimation of reinforcing area in the bottom of shear wall are not well addressed.

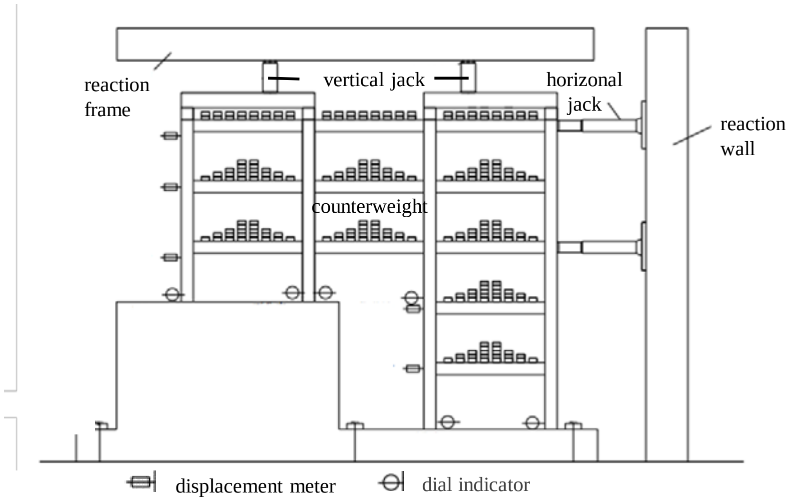


Fig. 8 Schematic diagram of test device

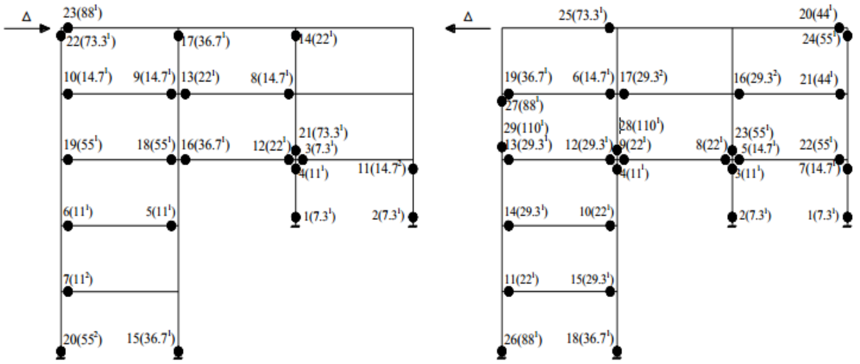


Fig. 9 – The hinge sequence diagram of test frame (blackeden circles denote plastic hinge; numbers before bracket denote hinge sequence; numbers in bracket denote the corressponding top displacement of frame; superscripts denote the corressponding cycle number)

In respect of elasto-plastic performance, Zhao [22] discovered that the upper embedding floor and the floor exactly above were normally believed to be weak-stories of frame structure supported by foundations with different elevations and the location of maximum story drift under frequent earthquake differed from that under rare earthquake, while merely by elastic analysis is unable to get this conclusion. From overall and local structural response, Zhao [37] studied on locations of failure, failure sequence and degree of damage of structures in mountainous terrain and proved its failure mechanism, namely, mixed hinge with beam and column, and indicated that damage of column hinge was more severe than beam hinge and earlier to occur and the amount of hinges was more than that of upper floors. Results of research from Zhao [37] were confirmed by typically low cyclic loading experiment of representative frame structure supported by foundations with different elevations [38], and the schematic diagram of test device is presented in Fig. 8, which showed that the whole structure represented well ductility but severe damages occurred at the bottom and top of columns located in upper embedding ends as shown in Fig. 9. By examining the collapse resistant capacity of frame structure supported by foundations with different elevations, Wu [39] indicated that failure initially occurred in upper embedding columns and demonstrated that its collapse resistant capacity was relatively lower than ordinary frame.

The range of study focusing on failure mechanism of structures in mountainous terrain is merely limited to frame structure and involved in comparatively less experimental simulation, so it is urgent to follow multi-structure types which learn well structures in mountainous terrain with mechanism of failure as a whole.

3.5 Irregularity of elevation and plane

Sharp change in stiffness and bearing capacity of upper embedding floor and torsional effect are main characteristics of structures in mountainous terrain.

For irregularity of elevation, Wang's study [20, 40-41] showed that the weak story of structures in mountainous terrain was not determined by lateral stiffness ratio and shear capacity ratio obtained by current code for seismic design [12-13]. It requires seeking for the suitable method to control vertical regularity. Upon the principle of equivalent top drift and method of D-value, the concept of equivalent column for computing stiffness of floors under upper embedding end and upper embedding floor counterpart was established, thus mutual control with intra-story to story stiffness ratio was proposed by studying the influence of different distribution of stiffness on seismic performance of structure supported by foundations with different elevations.

Based on results mentioned above, Zhou [42] compared structural performance with respect to three schemes including mutual control with intra-story to story stiffness ratio, equivalent stiffness ratio and corresponding part stiffness ratio. It indicated that corresponding part stiffness ratio for effectiveness of control was feasible and convenient to apply into practical design.

For issue of irregular torsion in structures in mountainous terrain, the study proposed by Shen and Fan [26-27] showed remarkable torsional effect in perpendicular to the direction of the slope where period ratio lost its function to assess the structural torsion. However, it should be pointed out that these results are obtained in terms of change in plan and elevation configurations rather than the intrinsic asymmetric distributions of mass, stiffness and strength.

3.6 Method of analysis and calculation

It is critical to employ suitable methods for structural analysis, and normally methods mainly include equivalent base shear method, mode-superposition response spectrum method, static pushover analysis method and dynamic time history analysis method.

Apparently, equivalent base shear method is not applicable to analyze structures in mountainous terrain because of the principle of the simplified computation. This method is applied well into mere situation where first modal vibration primarily contributes to entire structural response and the shape of modal vibration is approximately linear.

Mode-superposition response spectrum that involves dynamic characteristic is appropriate to be employed into multi-degree freedom system, likewise, the structures in mountainous terrain also are included. However, the consideration about the number of effective vibration mode is a matter to be concerned about.

Static pushover analysis is believed to be a general approximate method to estimate structural seismic performance, but Zhu [43] indicated that it was unreasonable to directly apply it into structures in mountainous terrain to estimate target displacement by capacity spectrum method recommended by ATC40 and revised target displacement method recommended by FEMA440, respectively, and proposed improved method for pushover by multi-level loading model and summarized the applicable condition of the improved method. There are still problems because of different elevations of embedding ends containing influence from different directions to pushover and high modes, proper hypothesis on lateral force and torsional effect, which are urgent to be further studied.

Dynamic time history analysis is well responsive to actual seismic response if employed under reasonable seismic input motion. Hence, it's necessary to place emphasis on input of selected ground motions.

Checking calculation of stability against overturning is an indispensable part of computation and analysis of structures in mountainous terrain. Different methods for checking calculation and determining tipping point of perpendicular to the direction of the slope and along the direction of the slope contribute to complexity of the calculation. By studying on anti-overturning performance along the direction of the slope, Zhao's investigations [23, 44] indicated that overturn resistance capacity was weakened in frame structure supported by foundations with different elevations compared to common structures and it was suggested that checking the stability against overturning of whole structure was necessary and presenting formula for checking along the direction of the slope, while that for perpendicular to the direction of the slope was still uncertainty.

3.7 Analysis of distinctive members

Compared with common structures, there are distinctive members in structures in mountainous terrain in terms of mechanics characteristics including beams with remarkable axial tension [34], joints bearing axial tensional force from beams [45] and vertical members with significant torsion [27].

Tensional beams, as special component, suffer huge axial forces when they are arranged in the frame structure supported by foundations with different elevations, which triggers problems about how to design tensional beams to ensure effective embedding between tensional beams and slope. Without tensional beams, axial forces of beams of upper embedding floor between grounding vertical members and un-grounding vertical members become significant, along with joints bearing axial tensional forces. Zhu's study [45] showed that there were similar patterns of mechanical mechanism and failure mechanism between these joints mentioned above and joints from ordinary frames, but shear capacity of core zone of joints from the frame structure supported by foundations with different elevations declines by examining results of simulation on mechanical mechanism and seismic performance. Therefore, whether or not measures are taken to enhance shear capacity of core zone of joints still needs further study. Likewise, studies on vertical members of upper embedding floor with remarkable torsion characteristic are also required to carry out.

4. Framework and main clauses of the specification for structural design

Research shows that whether the design of structures in mountainous terrain using the available engineering design software is partial to safety is inconsistent and difficult to evaluate [46]. Seismic design of structures in mountainous terrain following current specifications is unreasonable and unscientific. Structures in mountainous terrain need adaptable design basis.

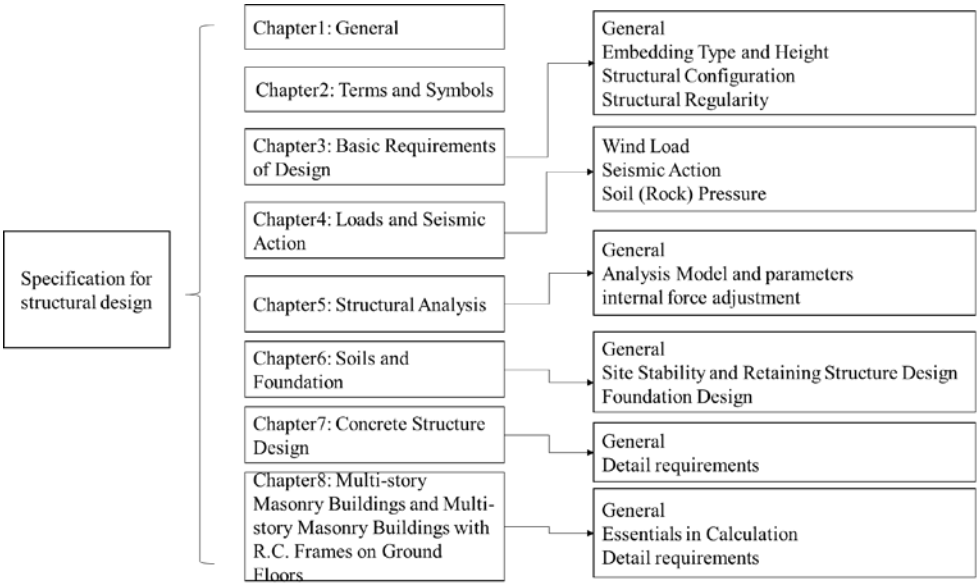


Fig. 10 – The framework of specification for structural design

Combined with current research and engineering experience, the specification for structures in mountainous terrain seismic design has been established. The main content of specification contains clauses about conceptual design, anti-seismic calculation and details of seismic design. There are seven chapters and the framework is as shown in Fig. 10.

Aiming at current research, main clauses are as follows:

The slope of structures in mountainous terrain must be stable and its deformation should be controlled strictly to ensure the whole performance. Stability checking calculation considering the load from structural foundation should be conducted for the slope within the scope of foundations and the slope acting as embedding ends.

Affected by the local topography, seismic parameters of rock slope adopts Wang's research results amplifying the design parameters of ground motion, while seismic parameters of soil slope will be interpolated on the basis of amplification of soil terrace referencing the interpolation of rock slope. Questions about multi-point excitation and dynamic soil pressure have not been ruled because of the lack of relevant research.

In the analysis of this kind structure, analytical model should be built according to practical constraint condition of ground connection and coincide with actual stress state. Spring element or lateral support is adopted to simulate the influence of soil. Torsional effect of structure subjected to bidirectional earthquake motion should be taken account of.

In anti-seismic calculation of structures in mountainous terrain, mode-superposition response spectrum method considering torsion coupling is suitable. For structure supported by foundations with different elevations, the number of considered vibration mode should ensure that effective modal participation mass is no less than ninety five percent of total mass. For high-rise building, time history analysis under frequent earthquake should be proceeded as supplement calculation.

In aspect of the control of irregularity, for practical purposes, the specification distinguishes between irregularity in plan and in elevation. Corresponding part stiffness ratio is adopted to control the irregularity in elevation.

Structural members with complicated stress, such as floor slab on the height of upper embedding end, beam-column joint with axial beam tension should be analyzed with finite element method to obtain detailed local stress. The check of design reinforcement may be proceeded according to stress analysis results.

5. Conclusions

This paper reports on research on the seismic behavior of structures in mountainous terrain and the main framework and clauses of specification for structural design.

Because of the complex embedding condition, it is not surprising that the seismic input and response of structures in mountainous terrain are different from common structures. The studies on seismic input mechanism, seismic behavior and special components have been proceeded and numerous results have been achieved. Primary understanding of characteristic of structures in mountainous terrain have been formed. Based on that, the specification for seismic design of structures in mountainous terrain has been established in spite of the incompleteness of research, which provides reasonable suggestions for design preliminarily.

Nevertheless, the further study of multi-type of this structure is needed, and problems of reasonable seismic input motion on different elevations and dynamic soil pressure associating with simplified analytical model are waiting to be solved. Experimental research about this kind of structure is rare and more special member tests are needed. In aspect of design, study on stability of slope and control index of irregularity is not enough, and details of seismic design are required to be improved.

6. Acknowledgements

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