Conclusions and Prospects

The slope stability under seismic effects is a both ancient and young subject. Because of its high complexity, the development till now is still immature. The special geographical and geological conditions and seismic configuration make it especially pertinent in China. Currently, the infrastructure construction such as highway, railway, and water conservancy is in rapid developing period, which draws higher demand on seismic design of slope engineering. Therefore, the slope stability under seismic effects is a crucial scientific problem urgently needs to be solved.

Part One: The Major Work and Conclusion of the Dissertation

Surrounding the national demands on infrastructure construction and reconstruction of Wenchuan seismic areas, and based on the investigated data of Wenchuan seismic slope damage, the research results of seismic array monitoring, the large-scale shaking table test and the numerical analysis, and technical measures like theoretical analysis, we explored the dynamic features of rock slope. On this basis, we take the most seriously hit bedrock and overburden slope in the earthquake as study object. This dissertation systematically studied on the scientific issues such as the rock slope dynamic response rules under seismic effects, the formation mechanism of landslide, and stability evaluation method as well as landslide hazard evaluation, which covered problems of slope stability under seismic effects on micro- and macro-aspects, and achieved some results and conclusions in the following aspects.

On Basic Dynamic Response of Rock Slope

(1) Based on the seismic array monitoring results of Zigong topography in “5.12 Wenchuan earthquake,” we conducted research on the seismic dynamic characteristics of slope topography from the aspects of amplitude response,

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Fourier spectrum, and response spectrum and achieved the following results: The component PGA of each direction on slope topography increases in nonlinear trend along elevation, the acceleration elevation amplification effects on EW direction were stronger than those on NS direction and those on UP direction were the weakest; for the horizontal acceleration, with the increase of elevation, the frequency components of Fourier spectrum around the slope natural frequency had amplification effects and showed the changing process from single peak to double peak, while the Fourier spectrum of vertical acceleration basically stayed unchanged; with the increase of elevation, the dynamic amplification coefficient of acceleration response spectrum increased, so did amplification effects, and the dynamic amplification coefficient of horizontal acceleration response spectrum was more than that of vertical acceleration response spectrum (Chap. 2).

(2) This chapter based on the large-scale shaking model test studied on the influence of bevel angle, seismic intensity, and seismic wave input type on rock slope dynamic characteristics, and its results showed: For mountains containing four slope surfaces, if we analyze with traditional method, i.e., using *X*, *Y*, and *Z* three direction coordinate system to analyze PGA elevation amplification effects, the results may be unilateral, so it suggested to use the three-dimensional local coordinate system. i.e., the free face direction, slope strike direction, and vertical direction of slopes; with the increase of bevel angles, the PGA elevation amplification effects in vertical direction will rise gradually, while at the same time, there exists a sudden increase turning point at bevel angles of 45° and a leveling off turning point at 50°. However, the PGA elevation amplification effects in slope strikes stay unchanged with the increase of bevel angles, and its steps are comparatively gentle; with the increase of seismic ground motion PGA, the peak acceleration elevation amplification effect decreases gradually, slope strike direction and vertical direction reduce gradually and show characteristics of magnitude saturation; the changes of Fourier spectrum frequency components of acceleration in free face direction (*L*), slope strike (*M*), and vertical direction (*N*) along elevation have certain regularity, i.e., with the increase of elevation, the slope soil has significant amplification effects for frequency components around its natural frequency range *f* and has filter effects for other frequency ranges; the changes of Fourier spectrum frequency components of acceleration in free face direction (*L*), slope strike (*M*), and vertical direction (*N*) along elevation are basically identical, and the correspondent response spectrum amplitude of predominant period has certain amplification effects along elevation, while for other period *T*, especially long period parts(low-frequency parts), there exists certain reduction effects. In addition, it has obvious peak phenomena for free face direction, while for slope strike direction and vertical direction, the peak phenomena are less obvious (Chap. 3).

(3) This chapter adopted both shaking table test and numerical analysis, and studied the influence of factors such as slope type, slope top local topography on the rock slope dynamic characteristics under seismic effects from the

perspective of time domain and joint time–frequency domain, and the results show: The acceleration Fourier spectrum along elevation of single- and double-sided high and steep slope surfaces all shows the changing rules of low-frequency components amplification, and the changing rules are influenced by slope topography and bevel angles. No matter for horizontal acceleration or vertical acceleration, the acceleration response spectrum along elevation of single-sided slope surfaces all shows single peak value, while that of double-sided slope surfaces followed the process of converting from single peak value to double peak value; no matter for single-sided high and steep slope or for double-sided high and steep slope, the PGA of different positions along elevation all amplifies to different extent, and it shows as follows: The amplification effects of double-sided high and steep slope on acceleration > the amplification effects of single-sided high and steep slope on acceleration; PGA amplification effects on slope surface > PGA amplification effects inside slope mass; the horizontal acceleration coefficient > the vertical acceleration coefficient, and acceleration coefficient on steep slope topography > acceleration coefficient on gentle slope topography; the local topography of slope top has significant influence on the intensity of seismic response, and the detailed rules are as follows: three peak slope top > double peak slope top > single peak slope top > flattop; and the high-frequency components of all of them gradually strengthen and the second step frequency becomes gradually obvious. At the same time, the characteristic periods of acceleration response spectrum of flattop, single, double, and three peak slopes are gradually transferred from long period to short period, and the double peak value of response spectrum gradually becomes obvious (Chap. 4).

On Theoretical Analysis of Rock Slope Acceleration Elevation Amplification Effects

(4) The double-sided rock slope acceleration elevation amplification effects time–frequency method is derived, based on elastic wave theory and horizontal slice method, through building force equilibrium differential equation of micro-unit, using Hilbert–Huang Transform and boundary conditions, and applying modal analysis method and normal mode theory. The rationality of this method is verified through shaking model test and numerical analysis. This method could not only take good consideration of the influence of three essential elements (PGA, frequency, and duration) on acceleration elevation amplification, but also explain the "whiplash effects" of slopes in the perspective of theoretical calculation. With the increase of seismic intensity, the shear displacement at slope top gradually increases, and the acceleration amplification coefficient gradually decreases; the shear displacement of slope mass is in nonlinear distribution along elevation and suddenly increases in multiple times; with the

increase of input wave frequency, the maximum shear displacement and acceleration amplification coefficient at slope top are distributed in saddle shape and reach the maximum value when input frequency value equals the maximum value of the natural frequency of slope mass; with the increase of bevel angles, the maximum shear displacement and acceleration amplification coefficient all gradually increase, and distribute in "step-form," i.e., in the ranges of 30°–45° and 50°–60°, the amplification coefficient all increases slightly, while in the range of 45°–50°, it increases suddenly. Through comparative analysis of high and steep rock slope time–frequency analysis method, with the calculation results of acceleration elevation amplification effects analysis method regulated in Code for Seismic Design of Buildings GB50011-2010, Specifications for Seismic Design of Hydraulic Structures DL/5073-2000, and Design Specification for Slope of Hydropower and Water Conservancy Project SL/386-2007, it is suggested that the calculation of rock slope acceleration elevation amplification coefficient in Seismic Code, Hydraulic Seismic Specifications, and Slope Design Specifications should take consideration of the influence of seismic intensity, so as to improve the rationality of structural seismic design (Chap. 5).

On Slope Deformation Characteristics and Formation Mechanism of Bedrock and Overburden Slopes

(5) This chapter focused on the two major landslide hazard spots on the left side of G213, built the numerical analysis model based on the shaking table test model, and used the new numerical calculation software—GDEM to simulate the whole process of deposit body landslides of single- and double-sided bedrock and overburden slopes from deformation to failure slip under intense earthquake, conducting comprehensive and in-depth research of slope deformation features and formation mechanism of bedrock and overburden slopes from the perspective of time domain and joint time–frequency domain. (1) The results show: No matter for single- or double-sided bedrock and overburden slopes, the landslides processes are basically the same, i.e., under effects of gravity and seismic power, tensile stress concentration firstly occurs at sliding mass top, causing deformation of sliding mass along sliding mass structural surface trailing edge, which causes tensile and shear failure points at this position. Then, with continuous seismic power, the shear failure points on sliding mass structural surface gradually develop to lock-fixed section of sliding mass leading edge with increasing amount of tensile failure points on sliding mass surface, which finally causes progressive damage of lock-fixed section, crack surface connecting to sliding zone and sliding mass slipping from shear crack into landslide; the inconsistency of motion between sliding bed and sliding mass, difference of seismic energy distribution and dissipation,

and decrease of sliding mass structural surface strength with increase of seismic intensity are three major controlling factors inducing landslides. When seismic ground motion acceleration is small, the instant frequency of horizontal acceleration inside the sliding bed and sliding mass stabilizes in a certain range with the former slightly higher than the latter. At the same time, the energy transmission coefficient on the sliding mass structural surface and the controlling frequency range of seismic energy inside the sliding mass all stabilizes in a certain range; with the increase of seismic intensity, the instant frequency of acceleration inside the sliding mass gradually decreases, and the energy transmission coefficient of sliding mass structural surface gradually decreases, with both finally approaching stability. Simultaneously, the controlling frequency range of seismic motion energy inside the sliding mass transferrs from high-frequency range to low-frequency range (Chap. 6).

On Seismic Stability Time–Frequency Analysis Method of Bedrock and Overburden Slope

(6) Based on elastic wave theory and general geological analysis model, this chapter derived seismic stability time–frequency analysis method of bedrock and overburden slope, and verified its rationality through shaking table test and numerical analysis results. This method could not only consider the influence of three essential elements (PGA, frequency, and duration) of SV wave on slope stability, but can also predict the safety of rock slopes, the happening time, and scale of landslides. At the same time, it can provide reference to supporting structure seismic time–frequency design in high intensive seismic regions; at the same time, the elasticity modulus of incident angle and cover layer has significant influence on the reflected and transmitted coefficients of structural surface and the energy reflected and transmitted coefficients (Chap. 7).

On Damage of Bedrock and Overburden Slope Landslide Induced by Earthquake

(7) On the basis of detailed research on landslide damage of Wenchuan earthquake, we focused on collecting and organizing the damage of bedrock and overburden slopes induced by earthquakes, and conducted statistical analysis results of correlation of the horizontal sliding distance L of 65 classic landslides with mountain height HL, tangent value of bevel angle $\tan\theta$, PGA, and landslide volume V, built the prediction model of horizontal sliding distance of bedrock and overburden slopes induced by Wenhcuan earthquake, and also

selected Donghekou large-scale landslide and other two commonly used sliding distance prediction model to verify the rationality and advantage of damage range prediction model of Wenchuan earthquake-induced bedrock and overburden slopes. The research results show: L is in positive correlation with PGA, HL, and V, and in negative correlation with tanθ; the probability of landslide happening at 1/3HL is 70.8 %, that of landslide happening at 0.3–0.6HL is 15.4 %, and that of landslide happening at 1/3HL is13.8 %, Therefore, most landslides happen at 1/3HL (Chap. 8).

(1)–(6) belong to research on micro-aspects, whose conclusion could be used to seismic design of concrete slope engineering; (7) belongs to macro-aspects, whose conclusion could be applied to decision on scheme of relocation and preventing collision, engineering management, and relocation range.

Part Two: Creativity of This Dissertation

The creativity of this dissertation is as follows:

(1) Tit proposed the double-sided rock slope acceleration elevation amplification effects time–frequency method, which can not only take good consideration of the influence of three essential elements (PGA, frequency, and duration) on acceleration elevation amplification, but also can provide theoretical supports to seismic design of rock and soil engineering in mountain regions in China (Chap. 5).

For slope deformation features and formation mechanism of bedrock and overburden slopes, this chapter conducted in-depth research from the perspective of joint time–frequency domain, promoted new analysis ideas to seismic mechanism of rock and soil engineering, which broke through the traditional analysis with sole reference to time-domain features or frequency-domain features (Chap. 6).

(2) This chapter promoted seismic stability time–frequency analysis method of bedrock and overburden slope, which could consider the influence of three essential elements (PGA, frequency, and duration) of seismic wave on slope stability (Chap. 7),
(3) This chapter promoted damage range prediction model of Wenchuan earthquake-induced bedrock and overburden slopes, which could consider four key factors including mountain height HL, tangent value of bevel angle tanθ, PGA, and landslide volume V, and it has high accuracy, and could provide scientific reference to decision on scheme of relocation and preventing collision, engineering management, and relocation range (Chap. 8).

Part Three: Problems and Prospects

This dissertation conducted some beneficial exploration on the aspects of slope dynamic characteristics, dynamic response, seismic design method, landslide mechanism, stability evaluation method and landslide damage range evaluation, and obtained some creative results. But as stated in the beginning of this dissertation, the slope dynamic stability problem is a complex subject concerning multi-crossed disciplines. Due to limits of knowledge of the author and research conditions, there is still imperfection in this dissertation, and there are problems worth further study and discussion.

(1) Conducting research on landslide damage mechanism, failure mode, motion features, and damage range;
(2) Conducting further study on constitutive relation of rock and soil mass, and building correspondent constitutive relation model of rock and soil mass based on different materials and loading effects, which has important value to both theoretical analysis and engineering application, and is a key direction for research of slope dynamic stability analysis;
(3) Conducting research on deformation mode and long-term evolutionary mechanism of rock slopes;
(4) Conducting research on slope stability judging system based on nonlinear characteristics of slope structural surface;
(5) Conducting research on theory of acceleration elevation amplification effects with full consideration of nonlinear characteristics of rock and soil mass.

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