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Dynamic calculation model and seismic response for frame supporting structure with prestressed anchors

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A dynamic calculation model of frame supporting structures with prestressed anchors for the slope stability is proposed. The frame and soil are closely contacted in the role of prestressed anchors and they cannot be separated along the whole slope. The lateral displacement of frame and soil is nearly in phase. The movement characteristic satisfies the theory of elastic foundation beam. The frame is treated with elastic foundation beam in this model. The influence of prestressed anchors is simplified as linear spring and damped system related with velocity. Under the condition of horizontal earthquake excitation, the equation of vibration response is established by using the model of dynamic Winkler beam and the analytical solutions are obtained for simple harmonic vibration. This method is applied to a case record for illustration of its capability, in order to verify the method, 3D nonlinear FEM (ADINA) is used to analyze the seismic performance of this case, the comparative results show that the design and the analysis are safe and credible by using the proposed method. The calculation model provides a new way for earthquake analysis and seismic design of slope stability supported by frame structure with prestressed anchors.

frame supporting structure with prestressed anchor, slope, dynamic calculation model, seismic performance, seismic design

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1 Introduction

Most area in the northwest of China is the mountainous area with the loess. The construction of high-grade roads, railways, and cities requires the engineers to consider slope protection. China is the area with high occurrence rate of earthquake. Its geological condition is complicated. Many roads and railways inevitably go through the seismic belt with high intensity. Massive geological hazards will occur due to the serious instability of the slope and this will lead to the blocking of rivers, traffic interruption and serious endanger to human life and property and become the large disaster that the human beings are unwilling to face. The landslide of the slope induced by earthquake is one of the major seismic geological hazards. In the mountainous area and the hilly areas, the landslides induced by earthquake have the features of wide distribution, large quantity and great hazard. For example, the earthquake with the magnitude of 6.5 occurring in Northridge in the America in 1994 triggered more than 11000 landslides whose area measured was up to 104 km^2. The economic loss amounted to 30 billion USD [1]. In 1973, the earthquake with the magnitude of 7.9 occurring in Sichuan Luhuo triggered 137 landslides whose area measured was up to 90 km^2. The death toll was 2175 [2]. The extraordinarily big landslide occurring in the ares of the Vaiont Reservoir in Italy in 1963 killed about 3000 people. Langjialang City in the down stream of the

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reservoir disappeared completely, which shocked the world and became one of the worst natural disasters in human history [3]. The landslide of Beacon Hill of Gansu in China in 1718 induced by the earthquake (M=7.5) killed 40000 people. Therefore, it can be concluded that if human is unable to fully understand features of the slope and the law of evolution, inestimable loss of life and property will be brought to human. The disasters caused by slope instability are shocking, so the slope dynamic analysis and seismic supporting design method has become one of the important issues for the field of the geotechnical engineering and the earthquake engineering [4,5].

In recent years, some new flexible supporting structures featuring the anchorage technology of rock-soil have overcome the shortcomings of traditional slope supporting structure, such as the restricted supporting height, high cost, heaviness and poor stability. The new flexible supporting structures play an important role in the slope supporting engineering [6–11]. Applying the technology into the slope supporting will have features of being light in structure, economical, beautiful, and excellent seismic performance. Measures for virescence may be taken, too. It is meaningful for ensuring the safe utilization of roads, railways, and buildings, preventing the landslide, and protecting the surrounding environment. The key of seismic design of frame supporting structure with prestressed anchors is the calculation of the internal force of frame. However, the study on the slope seismic mechanism and the dynamic analysis of the earthquake is still rare. In order to evaluate the anti-seismic performance of the frame supporting slope with prestressed anchors and guide similar engineering design, it is necessary and urgent to understand the dynamic features of the slope supported by the frame structure with prestressed anchors and the theory of the seismic design.

At present, common analytical methods for the seismic response of the frame slope supporting structure with prestressed anchors are boundary element method, fast Lagrangian method, and dynamic finite element method, and so on [12, 13]. Although these numerical methods can fully consider all factors, the modeling process is complex, the parameters are not easy to determine, and it is time-consuming for calculation. It is undoubtedly unpractical for the great number of engineering designs.

The dynamic Winkler foundation model is used in this paper. The frame is regarded as elastic foundation beam. The existence of the anchor is taken into consideration, in which its role is replaced by a spring and damper. This calculation model can accurately reflect the actual behavior of frame and realize the coordinate work calculation among anchors, frame and soil, which ensure the safety and reliability of the frame supporting structure with prestressed anchors under earthquake action. Finally, the finite element software ADINA [14] is introduced to simulate an engineering case to verify the accuracy of the method proposed in this paper. The calculation method provides a new way for the seismic analysis and design of the frame supporting structure with the prestressed anchors.

2 Model of the frame supporting structure with prestressed anchors

The frame supporting structure with prestressed anchors is a new light type supporting structure proposed in recent years, which consists of frame, retaining plate, anchors and back soil mass. In this kind of supporting structure, the frame includes vertical columns, horizontal beams and retaining plate, and these three parts form a vertical beam slab structure similar to the superstructure, in which the anchor head and the frame are connected at the intersection of beam and column connection, the anchorage segment is anchored in soil. The earth pressure acting on the retaining plate is transferred to the anchorage segment through anchor head, then transferred to the cement mortar through the bond strength around the steel bar. Finally, it is transmitted to the stable soil of anchorage zone through the frictional force of the soil surrounding the anchorage zone. The elevation drawing and the profile of frame supporting structure with prestressed anchors are shown in Figures 1 and 2 respectively.

3 Establishment of the dynamic model of frame supporting structure with prestressed anchors

The frame closely contacts the soil on the slope. The lateral displacement of frame and soil is nearly in phase, which conforms to the working principle of elastic foundation beam, the numerical simulations and laboratory tests indicate that the frame deformation is the main bending deformation. In order to simplify the calculation, the torsional effect between frame beams and columns is not taken into

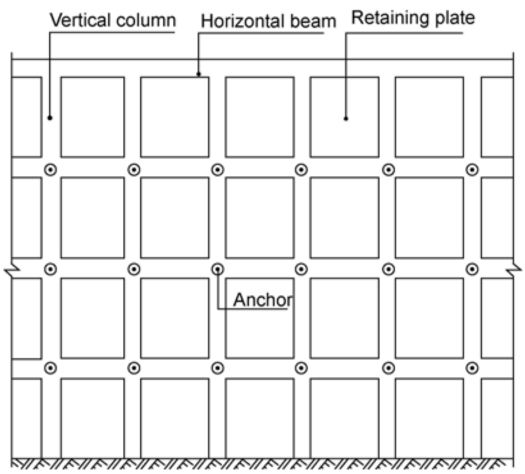

Figure 1 Elevation drawing of frame supporting structure with prestressed anchors.

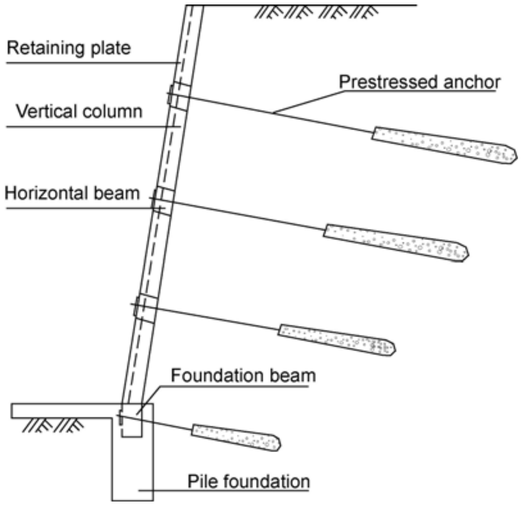

Figure 2 Profile of frame supporting structure with prestressed anchors.

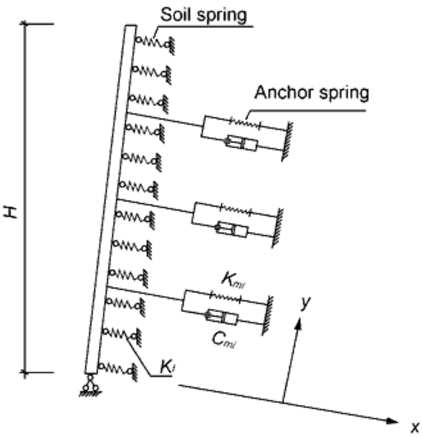

Figure 3 The calculating schematic diagram of frame supporting structure with prestressed anchors.

account, and the horizontal beams and the vertical columns are regarded as a series of independent continuous beams respectively.

In this paper, the following assumptions are adopted in the establishment of the horizontal seismic dynamic model of the frame structure with prestressed anchors.

(1) The foundation soil is uniform and elastic.

(2) The concrete frame is isotropic homogeneous elastic body.

(3) The frame keeps close contact with the soil on the slope during the vibration.

(4) The deformation of frame beams and columns satisfies the plane section assumption.

(5) The frame structure with prestressed anchors is more applicable to high and steep slope with the slope angle β of 75° to 90°. The component of the horizontal seismic wave in the direction parallel to the slope is minor and can be neglected.

(6) The initial state is static.

In this paper, only the horizontal seismic action is taken into consideration. It can be found through the analysis that the reaction force of each supporting point of the horizontal frame beam and the foundation is the same. The dimension of the slope along the direction of the frame beam is comparatively large and the torsional effect between frame beams and columns is neglected. The beam and column of frame can be decomposed into independent calculating elements to simplify the problem of plane strain. The frame column is the major bearing member and the frame beam only has the function of spatial coordinate work. Therefore, in order to be more simplified, the dynamic motion equation is established for the frame column, in which the frame column is simplified as a Winkler beam with multi-point discrete supports [15, 16]. The existence of the anchors is considered, in which its function can be substituted by a spring and damping system. The coordinate system is shown in Figure 3, the equation is:

$$EI_{\mathrm{c}}\frac{\partial^4 u}{\partial y^4}+m\frac{\partial^2 u}{\partial t^2}+k_{\mathrm{f}}u=-m\frac{\partial^2 u_{\mathrm{g}}\sin\beta}{\partial t^2}+\sum_{i=1}^{N}F_i(t)\delta(y-y_i)$$

$$(0\leqslant y\leqslant H/\sin\beta,\ t\geqslant 0),\tag{1}$$

where EI_{c} is the bending stiffness of frame column; m is the mass of unit length of column; u is the displacement of frame column; k_{f} is the elastic foundation coefficient; u_{g} is the horizontal seismic wave; β is the slope angle; N is the number of anchors; y_i is the vertical coordinate of the ith row anchor position; and $F_i(t)$ is the supporting reaction force of the ith row anchor at the position y_i. The value of $F_i(t)$ is

$$F_i(t)=C_{mi}\frac{\mathrm{d}u(y_i,t)}{\mathrm{d}t}+K_{mi}u(y_i,t),\tag{2}$$

where K_{mi} is the elastic coefficient of anchor (see ref. [17] for the value); C_{mi} is the damping coefficient of the anchor (see refs. [18,19] for the calculation method of damping). The value of C_{mi} is as follows:

$$C_{mi}=2\bar{\rho}_i B(V_{\mathrm{s}}+V_{\mathrm{p}}),\tag{3}$$

where V_{s}, V_{p}, B, and $\bar{\rho}_i$ are the shear wave velocity and the compressive wave velocity of soil, the equivalent width of anchors and the surrounding soil system, the equivalent density of anchors and soil respectively.

Boundary conditions: The bottom of frame supporting structure with prestressed anchors is regarded as a fixed hinge, and the upper is free, namely, when $y = 0$,

$$u|_{y=0}=0,\quad EI\frac{\partial^2 u}{\partial y^2}|_{y=0}=0;$$

when $y = H/\sin\beta$,

$$EI\frac{\partial^2 u}{\partial y^2}\Big|_{y=H/\sin\beta} = 0,\ EI\frac{\partial^3 u}{\partial y^3}\Big|_{y=H/\sin\beta} = 0.$$

Initial conditions:

$$u\big|_{t=0} = 0,\ \frac{\partial u}{\partial t}\Big|_{t=0} = 0.$$

4 Analysis of the dynamic response of the frame supporting structure with prestressed anchors under the harmonic earthquake wave

The actual seismic acceleration is the random vibration. In order to provide convenience for the engineering analysis and design, the random seismic wave is adjusted to the regular sine wave by using the equivalent acceleration method. Moreover, a formula revised through introducing the earthquake magnitude according to many soil dynamics tests carried out by Kohji is adopted [20]:

$$a(t) = 0.1(M-1)a_{\max}\sin\frac{2\pi}{T_{\mathrm{g}}}t, \tag{4}$$

where $a_{\max}$ is the peak of the seismic acceleration; T_{g} is the predominant period of the seismic motion; and M is the magnitude.

Assuming $\frac{\partial^2 u_g}{\partial t^2} = a(t)$, and substituting it into formula (1), we then obtain:

$$EI\frac{\partial^4 u}{\partial y^4} + m\frac{\partial^2 u}{\partial t^2} + k_{\mathrm{f}}u = -0.1m(M-1)a_{\max}\sin\frac{2\pi}{T_{\mathrm{g}}}t\sin\beta + \sum_{i=1}^{N}F_i(t)\delta(y-y_i)\quad (0 \leqslant y \leqslant H/\sin\beta,\ t \geqslant 0). \tag{5}$$

The analytical solution of eq. (5) cannot be found because of the coupled motion of the anchor and the frame. In order to simplify eq. (5) and get the analytic solution, refer to the decoupling method between the upper structure and the pile foundation and establish the equation of motion for the anchor and equivalent frame at the anchor head through the equivalent transformation, in which the equivalent frame is rigid block and the anchor is viscoelastic support. The influence of the beam and column of the frame and the elastic foundation is considered, too. The stiffness is added into the anchor support, as shown in Figure 4. Therefore, the equivalent equation of motion of each anchor at the support y_i can be obtained. Decouple and simplify formula (5) and establish an equation of motion as follows:

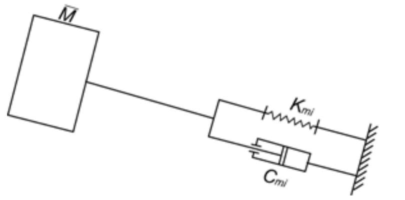

Figure 4 The calculating schematic diagram of equivalent frame and supporting anchors.

$$\bar{M}\frac{\mathrm{d}^2 u(y_i,t)}{\mathrm{d}t^2} + C_{mi}\frac{\mathrm{d}u(y_i,t)}{\mathrm{d}t} + \bar{K}_{mi}u(y_i,t) = -0.1\bar{M}(M-1)a_{\max}\sin\frac{2\pi}{T_g}t\sin\beta, \tag{6}$$

where $\bar{M}$ is the equivalent mass at the anchor head (define the equivalent mass according to code [21] approximately) and $\bar{K}$ is the total stiffness of the anchor, frame, and equivalent elastic foundation whici is defined according to the following formula:

$$\bar{K}_{mi} = K_{mi} + k_{\mathrm{f}}S_{\mathrm{h}}S_{\mathrm{v}} + 2\left(\frac{12EI_{\mathrm{b}}}{S_{\mathrm{h}}^3} + \frac{12EI_{\mathrm{c}}}{S_{\mathrm{v}}^3}\right), \tag{7}$$

where EI_{b} is the bending stiffness of the frame beam; S_{h} is the horizontal spacing of anchors; and S_{v} is the vertical spacing between anchors.

According to the basic assumption (6) and the initial condition, the solution of equation is set as follows:

$$u(y_i,t) = G_1\sin\frac{2\pi}{T_g}t + G_2\cos\frac{2\pi}{T_g}t. \tag{8}$$

The following formula can be obtained through solving:

$$G_1 = \frac{\left[\bar{M}\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2 + \bar{K}_{mi}\right]0.1\bar{M}(M-1)a_{\max}\sin\beta}{C_{mi}{}^2\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2 + \bar{K}_{mi}\bar{M}\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2 - \bar{K}_{mi}{}^2 - \bar{M}^2\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^4 - \bar{M}\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2\bar{K}_{mi}}, \tag{9}$$

$$G_2 = \frac{0.1\bar{M}(M-1)a_{\max}C_{mi}\frac{2\pi}{T_{\mathrm{g}}}\sin\beta}{C_{mi}{}^2\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2 + \bar{K}_{mi}\bar{M}\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2 - \bar{K}_{mi}{}^2 - \bar{M}^2\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^4 - \bar{M}\left(\frac{2\pi}{T_{\mathrm{g}}}\right)^2\bar{K}_{mi}}. \tag{10}$$

Before solving formula (5), we should solve the secular equation and the characteristic value of the homogeneous equation corresponding to formula (5). The secular equation can be obtained through using the separation of variables:

$$\phi(y) = A_1 \sin ay + A_2 \cos ay + A_3 \operatorname{sh} ay + A_4 \operatorname{ch} ay. \quad (11)$$

Substituting it into the boundary condition obtains the characteristic function as follows:

$$\phi_n(y) = \sin a_n y + \frac{\sin(a_n H/\sin\beta)}{\operatorname{sh}(a_n H/\sin\beta)} \operatorname{sh} a_n y, \quad (12)$$

a_n in the formula will be defined by the frequency equation (13).

$$\cos(a_n H/\sin\beta)\operatorname{sh}(a_n H/\sin\beta) - \sin(a_n H/\sin\beta)\operatorname{ch}(a_n H/\sin\beta) = 0. \quad (13)$$

Assume $u(y,t) = \sum_{n=0}^{\infty} Y_n(t)\phi_n(y)$ and substitute it into the basic equation of formula (5). Multiple two sides with $\phi_n(y)$ and integrate in the interval $[0, H/\sin\beta]$. Use the characteristics of δ function and the orthonormality of the intrinsic function:

$$M_n \ddot{Y}_n(t) + (\omega_n^2 M_n + K_n) Y_n(t) = P_n(t), \quad (14)$$

where

$$M_n = \int_0^{H/\sin\beta} m\phi_n^2(y)\,\mathrm{d}y, \quad (15)$$

$$K_n = \int_0^{H/\sin\beta} k_f \phi_n^2(y)\,\mathrm{d}y, \quad (16)$$

$$\begin{aligned} P_n(t) &= \int_0^{H/\sin\beta} \phi_n(y)\left[-0.1m(M-1)a_{\max}\sin\frac{2\pi}{T_g}t\sin\beta + \sum_{i=1}^{N} F_i(t)\delta(y-y_i)\right]\mathrm{d}y \\ &= \int_0^{H/\sin\beta} \phi_n(y)\left(-0.1m(M-1)a_{\max}\sin\frac{2\pi}{T_g}t\sin\beta\right)\mathrm{d}y + \sum_{i=1}^{N} F_i(t)\phi_n(y_i). \end{aligned} \quad (17)$$

As the initial condition is static, according to Duhamel integral expression, the following formula can be obtained:

$$Y_n(t) = \frac{1}{M_n \bar{\omega}_n} \int_0^t P_n(\tau) \sin \bar{\omega}_n (t-\tau)\,\mathrm{d}\tau, \quad (18)$$

where

$$\bar{\omega}_n^2 = \omega^2 + \frac{K_n}{M_n}. \quad (19)$$

In general, a comparatively good approximate solution may be obtained only by considering the first few modes.

5 Case analysis and numerical verification

5.1 Project background

For the slope supporting of Lanzhou Xiaxiyuan Fund Development Building, the slope is supported by the frame structure with prestressed anchors. The supporting height is 12 m. The importance coefficient is 1.0 and the safety coefficient is 1.3. The site is of category II. The seismic fortification intensity is 8 degrees. The parameters of the slope soil are listed in Table 1.

5.2 Supporting plan and design results

The frame supporting structure with prestressed anchors is adopted. The concrete grade is C30. The pseudo-static limit equilibrium method is adopted to carry out the design of the supporting structure and the seismic stability analysis [22]. Tables 2 and 3 show the final design results and Figure 5 illustrates the profile of the design of frame supporting structure with prestressed anchors.

5.3 Seismic dynamic response analysis of the frame

The calculating parameters are chosen as follows: the unit weight of the concretes is 25 kN/m³, the elasticity modulus of the concrete is $E = 3\times10^4\ \mathrm{N/mm^2}$, the combination elastic modulus of anchor is $E_c = 8\times10^9\ \mathrm{N/mm^2}$, the equivalent width of anchors and the surrounding soil system is $B = 2.5$ m, the elastic foundation coefficient is $k_f = 3.5\ \mathrm{N/mm^2}$, and the peak of the seismic acceleration is $a_{\max} = 0.2\ g$. According to the site category, the design characteristic period of ground motion is $T_g = 0.5$ s, the magnitude is $M = 7$, shear wave velocity is $V_s = 260$ m/s, and the compressed wave speed is $V_p = 430$ m/s.

Table 1 Slope soil parameters

Cohesion (kPa)	Internal friction angle (°)	Unit weight (kN·m^{-3})	Limit interface friction (kPa)	Slope angle (°)	Poisson's ratio	Elastic modulus (Pa)
16	20	16.5	50	80	0.3	2000000

Table 2 Design results of frame

Column				
Spacing	Section size (b×h)	Positive reinforcement	Negative reinforcement	Hoop reinforcement
2.5 m	400 mm × 300 mm	3Φ18	3Φ20	ϕ8@200
Beam				
Spacing	Section size (b×h)	Positive reinforcement	Negative reinforcement	Hoop reinforcement
2.5 m	300 mm×300 mm	3Φ22	3Φ22	ϕ8@200
Retaining plate				
Thickness (mm)		Longitudinal reinforcement		Transverse reinforcement
100		ϕ8@200		ϕ8@200

Table 3 Design of anchor

Anchor layers	Anchor position (m)	Freedom length (m)	Anchorage length (m)	Anchor hole diameter (mm)	Anchor bar diameter (mm)
1	2.0	7.0	11.0	200	36
2	4.5	5.0	11.0	200	36
3	7.0	3.8	11.0	200	36
4	9.5	2.5	11.0	200	36

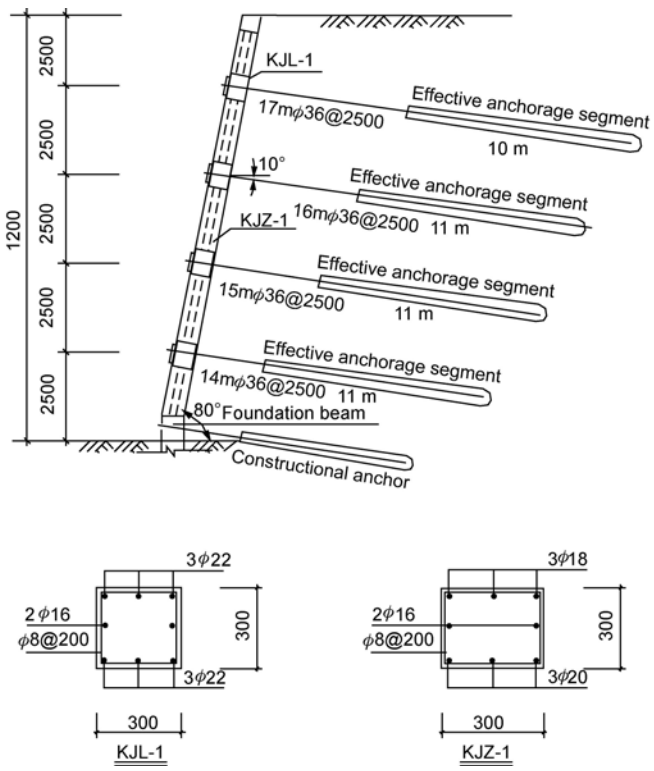

Figure 5 Profile of supporting structure.

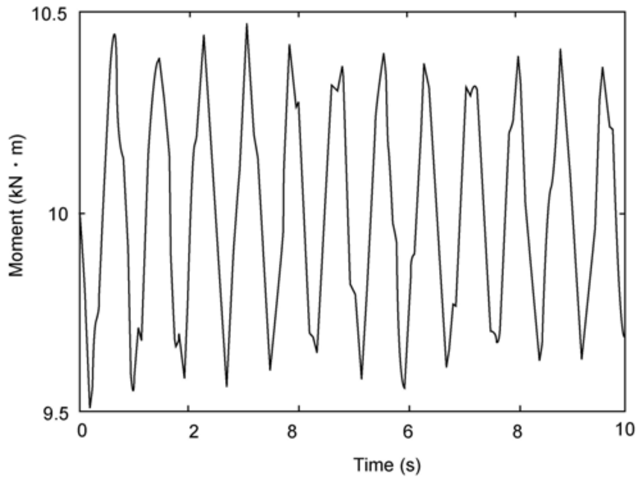

Figure 6 Moments time history at y=1.25 m.

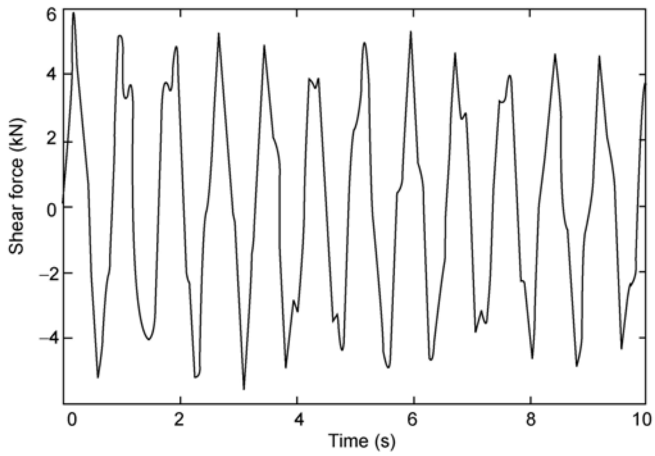

Figure 7 Shear forces time history at y=1.25 m.

Because the dynamic equation of the frame supporting structure with prestressed anchors is established under the condition of static equilibrium, the overall seismic response is the total internal force of the static force and the dynamic response [15] (see ref. [23] for the static force calculation).

Figures 6–9 show the moment and the shear force time history of the frame column when y=1.25 m and y=10 m. These figures show that the moment and the shear force of the frame fluctuate obviously with the intensity of the seismic wave. When y=1.25 m, the maximum amplitude of the moment is 10.43 kN·m. Compared with that before the earthquake, it is magnified by 6%. The maximum amplitude of the shear force is 5.73 kN, which is 5.7% magnified compared with that before the earthquake. When y=10 m,

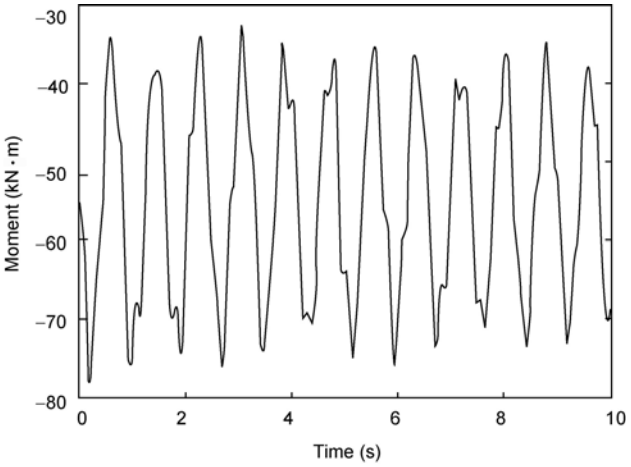

Figure 8 Moments time history at y=10 m.

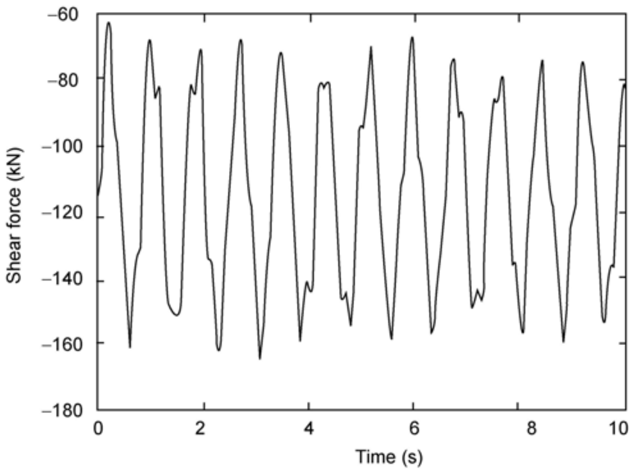

Figure 9 Shear forces time history at y=10 m.

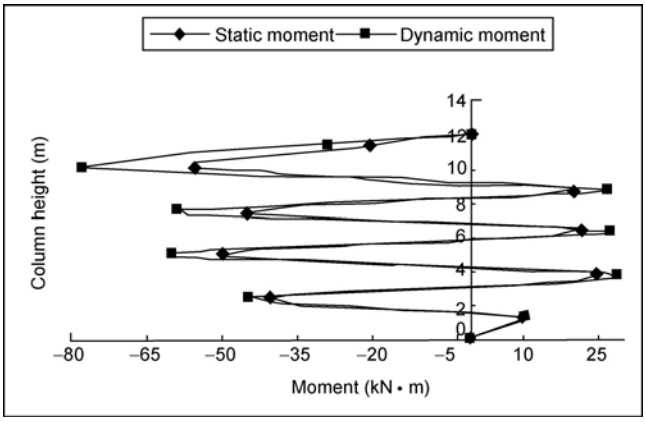

Figure 10 Peak moments for column of frame supporting structure with prestressed anchors.

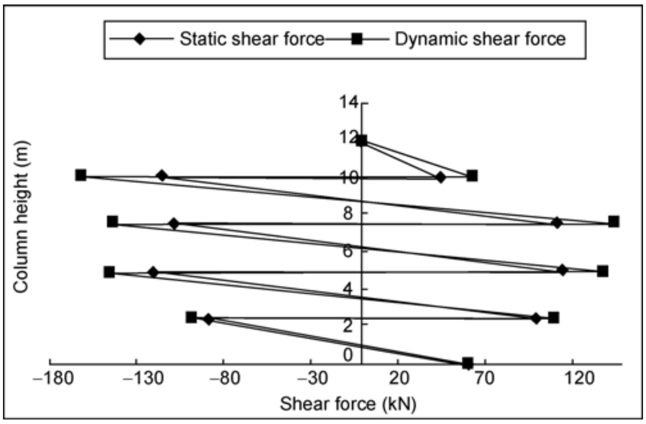

Figure 11 Peak shear forces for column of frame supporting structure with prestressed anchors.

the maximum amplitude of the moment is 77.5 kN·m. Compared with that before the earthquake, it is magnified by 10%. The maximum amplitude of the shear force is 163 kN, which is 36% magnified compared with that before the earthquake.

Figures 10 and 11 give the envelope diagrams of the moment and shear force of the frame column under static and dynamic action. It can be seen from Figures 10 and 11 that the moment and the shear force are small in the upper and lower parts of the column but larger in the middle part. The negative moment of the support position is obviously larger than the midspan positive moment. The peak of the moment and the shear force appear at the anchor position of the first layer, which is mainly caused by the cantilever of frame column. The peak of the dynamic moment is 77.5 kN·m, which is 22.5 kN·m more than the static moment. The peak of the dynamic shear force is 163 kN, which is 41 kN more than the static shear force. The increment of the dynamic moment and shear force will increase with the slope height. However, the design of traditional rigid retaining wall is based on pseudo-static method, the increment of the dynamic moment and shear force is the constant. There is obviously irrational.

5.4 Numerical verification

In order to verify the rationality of the proposed method, numerical simulation is conducted with the large-scale finite element software ADINA. The loading procedure of the simulation can be divided into three steps including applying the weight, applying the tectonic stress field, and inputting seismic wave. First, the static analysis is conducted, then the dynamic analysis for the model is carried out. The three-dimensional entity 8-node element is used for the soil, rebar element for the anchor rod, beam element for the frame, and shell element for the retaining plate. Assume that the material of the frame and the retaining plate has the linear elasticity. The contacting element is used among the soil, the retaining plate, and the frame. The dimensions of the model are 60 m×30 m×25 m. The number of the frame unit is 12. As the beam element has 6 degrees of freedom and the entity element has 3 degrees of freedom, two types of elements cannot work coordinately. In order to make the elements with different degrees of freedom work coordinately and the beam element transfer the moment more accurately, let the displacements of the beam element node and the entity element node be the same through the node coupling. Derive the equation of constraint imposed between the beam element and the entity element. ADINA provides two types of the dynamic boundary: cutting boundary and viscous boundary. As the cutting boundary will lead to fuzzy result, the viscous boundary is used in this paper. The inputting seismic wave is the sine wave. The inputting seismic wave excitation can be obtained from formula (4) as shown in Figure 12. The finite element model established is shown in Figures 13 and 14.

From Figure 15, it can be found that the results of the two calculating methods show good agreement. The calculation results of the finite element method are a little more than the calculation results of the proposed method in this paper. Table 4 gives the moments of the support position and the midspan. Through the comparison, the error is within 5%, which is caused by the frame beam and the simplification of the calculation model. However, it is acceptable for the rock-soil engineering design and the analysis. The seismic design of the frame column should take appropriate increment coefficient by the multiplier in order to consider the effect of the frame beam. Figure 15 shows that the moments of the top and the bottom of the slope are not zero because the edge sealing beam on the top of the slope and the foundation beam at the bottom of the slope are taken into consideration during the modeling of the finite element. The values are minor and can be neglected. Therefore, the calculation model established in this paper is rational and feasible.

5.5 Checking of the frame seismic capacity

According to the China Code for Seismic Design of Architecture Structures (GB50011-2002) [21], the bearing capacity of the frame column is

$$M^{c} \leqslant \gamma_{RE} M^{r}, \tag{20}$$

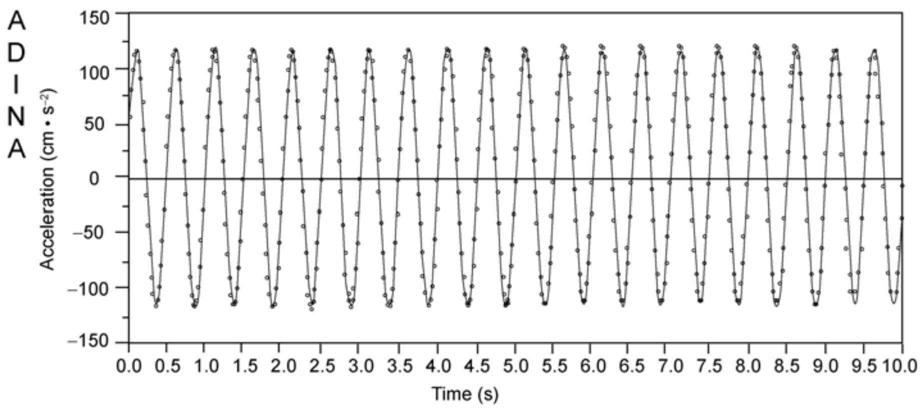

Figure 12 Sinusoidal horizontal earthquake excitations.

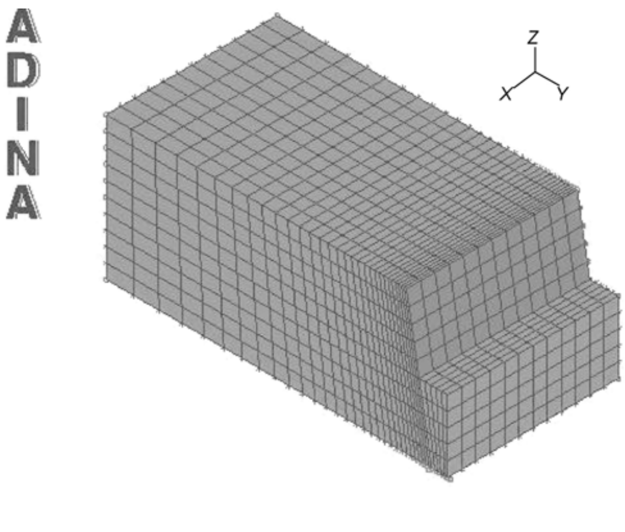

Figure 13 The finite element mesh of computing domain.

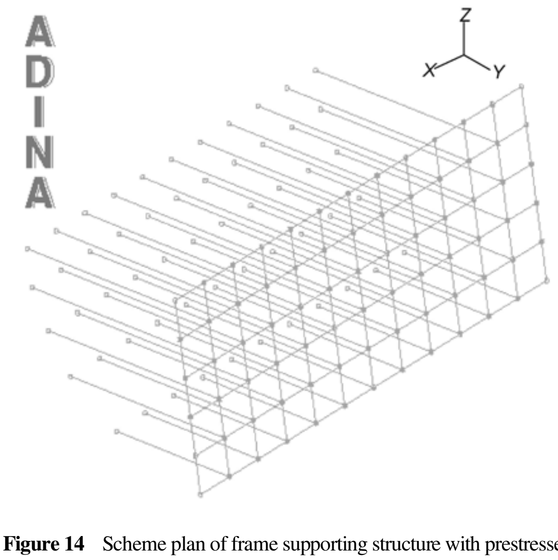

Figure 14 Scheme plan of frame supporting structure with prestressed anchors.

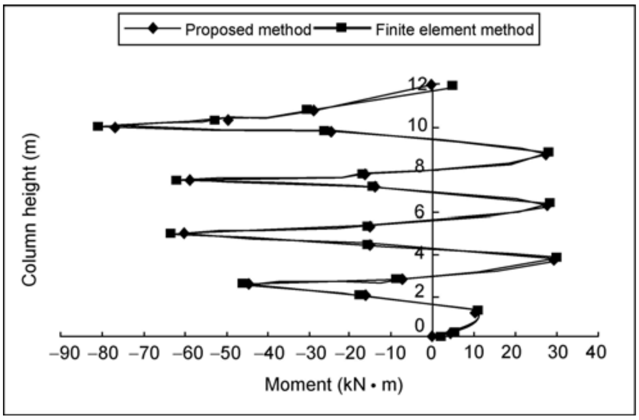

Figure 15 Peak moments for column of frame supporting structure with prestressed anchors.

where M^{c} is the design value of the combined moment of the section, γ_{RE} is the seismic adjustment coefficient for the bearing capacity (usually 0.85), and M^{r} is the bearing capacity of the section. Here $\gamma_{RE}M^{r}=0.85\times 67.9=57.7$ kN m, it cannot satisfy the requirement. Therefore it should be redesigned and the negative reinforcement is designed as 3Φ25. The calculation result is $\gamma_{RE}M^{r}=85$ kN m, which satisfies the requirement. The checking of the positive moment also satisfies formula (20).

The relative height of the compressed zone reflects the ductility of members. According to the code, when seismic level is I

$$x_0/h_0\leqslant 0.25; \tag{21}$$

when seismic level is II or III

$$x_0/h_0\leqslant 0.35. \tag{22}$$

The defense of this project is determined according to seismic level II. According to the sectional design, $\frac{x_0}{h_0}=\frac{77.3}{265}=0.29$ satisfies the requirement.

In order to prevent the incline compression damage caused by the insufficient dimension of the concrete column section under the earthquake action, following requirements should be satisfied.

For column with shear span ratio more than 2

$$V\leqslant\frac{1}{\gamma_{RE}}\left(0.2f_c bh_0\right); \tag{23}$$

for column with shear span ratio less than 2

$$V\leqslant\frac{1}{\gamma_{RE}}\left(0.15f_c bh_0\right), \tag{24}$$

where V is the design value of the combined shear force of the section; f_c is the design value of the axial compression strength of the concrete; b is the width of the section; and h_0 is the effective height of the section.

Through calculation, the shear span ratio is less than 2. $\frac{1}{\gamma_{RE}}\left(0.15f_c bh_0\right)=267.5$ kN satisfies formula (24).

6 Conclusion

The following conclusions can be obtained through the study on the dynamic calculation model and seismic response for frame supporting structure with prestressed anchors:

(1) Based on the dynamic Winkler foundation model, a simplified dynamic calculation model for earthquake of frame supporting structure with prestressed anchors is established. Under the horizontal earthquake excitation, the analytical solution of the frame seismic response is obtained.

(2) The seismic displacement response and internal force response of the frame, the axial force increment response of the anchor near the failure surface, the peak response of earth pressure as well as the distribution laws of the dynamic coefficient along the vertical direction of the slope can be obtained with the established model.

(3) The calculation model given can more accurately reflect the actual dynamic behavior of the frame supporting structure with prestressed anchors and realize the calculation of coordinating function of the anchor, frame and soil, and ensure the safety and reliability of the supporting structure. It is also able to provide qualitative understanding and physical explanation for the dynamic response of the frame supporting structure with prestressed anchors, describe the dynamic interaction between the structure and the soil under the earthquake excitation, and reduce the calculation amount of numerical methods.

Table 4 Frame column internal force

Column height (m)	0	1.25	2.5	3.75	5.0	6.25	7.5	8.75	10.0	11.25	12.0
Proposed method (kN·m)	0	10.43	–44.05	28.75	–60.02	27.50	–58.50	27.03	–77.50	–29.01	0
Finite element method (kN·m)	2.11	11.025	–46.20	30.19	–63.04	28.88	–61.43	28.35	–80.85	–30.45	5.12

(4) The analysis indicates that the internal force of the frame column is the primary factor of designing the frame. The section dimension and the reinforcement ratio are the major factors of the ductility design of frame.

(5) The seismic analysis and design are conducted according to the case. The large-scale nonlinear finite element software ADINA is used to verify the calculation model. The result indicates that the calculation model is feasible for the dynamic design and analysis of the slope with homogeneous soil. The calculation methods provide a new way for the seismic analysis and design of the frame supporting structure with prestressed anchors.

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