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Seismic reliability of concrete rectangular liquid-storage structures

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Abstract. To analyze the seismic reliability of concrete rectangular liquid storage structures (CRLSSs), assuming that the wall thickness and internal liquid depth of CRLSSs are random variables, calculation models of CRLSSs are established by using the Monte Carlo finite element method (FEM). The principal stresses of the over-ground and buried CRLSSs are calculated under three rare fortification intensities, and the failure probabilities of CRLSSs are obtained. The results show that the seismic reliability increases with the increase of wall thickness, whereas it decreases with the increase of liquid depth. Between the two random factors, the seismic reliability of CRLSSs is more sensitive to the change in wall thickness. Compared with the over-ground CRLSS, the buried CRLSS has better reliability.

Keywords: concrete rectangular storage structure; seismic reliability; liquid depth; wall thickness

1. Introduction

With the development of the petroleum and chemical industry, the concrete rectangular liquid storage structures (CRLSSs) are broadly applied to these industries, mainly for reserve rinsing and storage of sewage, petroleum and chemical liquid. However, the damage of this type of structure under the seismic load has an extremely serious influence on both industrial production and people's lives. Thus, it is of great significance to study the seismic reliability of the structure and to provide a relevant theoretical basis for the seismic design for such structures.

At present, many scholars have performed a variety of research studies in related fields. Zhang *et al*. (2016) established models of rectangular and circular CRLSSs with identical wall thickness and liquid height by finite element method (FEM) and studied the seismic responses of different CRLSSs numerically by applying the fluid-solid coupling solver. Shekari (2018) investigated the numerical seismic response of rectangular liquid tank system isolated by bilinear under three real earthquakes with different frequency characteristics. Wang and Lei (2011) studied the nonlinear seismic response and the failure mechanism of a CRLSS by FEM. Du *et al*. (2008) used numerical simulations to study the fluid solid coupling dynamic response law of the CRLSS under unidirectional and multidirectional seismic coupling. Seleemah and El-Sharkawy (2011) considered three types of isolation systems and investigated the seismic responses of base-isolated broad and slender cylindrical liquid storage ground tanks. Curadelli (2013) investigated seismic performance of cylindrical liquid storage tanks base-isolated by bilinear bearings. Park *et al*. (2016) investigated dynamic behavior characteristics of a cylindrical liquid storage tank under horizontal earthquake excitation, which is includes beam-type and oval-type vibration. Khanmohammadia *et al*. (2017) investigated the effect of amplitude and frequency of input excitation on model responses buried concrete rectangular liquid storage tanks with regard to the water level, the buried depth, and the density of surrounding soil. Zhao and Cheng (2015) analyzed the fluid-solid-interaction (FSI) resonance response of the rubber isolated CRLSS. Ghaemmaghami and Kianoush (2010) considered the shock and convection responses of the tank system, used linear free surface boundary conditions to simulate sloshing and studied two different finite element models of water tank structures. Faltinsen *et al*. (2000, 2003) systematically studied the nonlinear large sloshing of liquid in a CRLSS. Cheng *et al*. (2018a, b) studied the liquid sloshing problem of concrete rectangular storage structure with a vertical baffle. Considering nonlinear elasticity of concrete, Cheng *et al*. (2018c) analyzed seismic response of base-isolated CRLSS. Lakhade *et al*. (2018) studied damage states of yielding and collapse for elevated water tanks supported on reinforced concrete (RC) frame staging. Based on the analysis of the seismic response of defective oil storage tanks with the additional mass method, Xu and Lou (2018) calculated the reliability of oil storage tanks with and without initial geometric defects under random earthquake. Aliche *et al*. (2019) proposed a probabilistic approach by considering the hydraulic static load inside the tank and the seismic acceleration of the soil to analyze the reliability of RC tank. Saha and Matsagar (2015) evaluated reliability of base-isolated liquid storage tanks under random base excitation in horizontal direction considering uncertainty in the isolator parameters. Marsili *et al*. (2017) presented the

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seismic reliability assessment of a concrete water tank based on the bayesian updating of the finite element model. Wang *et al*. (2015) established limit state equation to obtain the reliability corresponding to the structural failure criteria.

In summary, the existing literature contains extensive research on seismic response studies of the CRLSS, but there is relatively little research on the reliability of structures with special functions such as CRLSS. Further research is required in the process of seismic reliability analysis because of the complexity and variability of random factors. Therefore, this paper uses the FEM to establish an analysis model of CRLSSs. Using this model, the seismic reliability of CRLSSs is studied, and the main factors affecting the reliability of CRLSSs are proposed.

2. Monte Carlo FEM

At present, the reliability algorithm of a structure mainly includes the first-order second-moment method, higher-order moment method, response surface method, and Monte Carlo method.

The Monte Carlo FEM, which is based on the combination of Monte Carlo method and stochastic FEM (Liu 2003), is used in this paper. The method is the most accurate, intuitive and effective statistical calculation method of structural reliability. The basic principle is that the ratio of failure variables to the total number of variables is calculated to determine its failure probability by using a large sampling of random variables. This method avoids the complexity of the nonlinear and limit state curved surface of functional functions and has been widely used with the development of computer technology.

First, a series of random numbers are formed by each random variable based on the uniform distribution. The multiplicative congruence method is applied to uniformly distributed random numbers in the (0,1) interval:

$$X_{i+1} = \left(ax_i + c\right)\left(\operatorname{mod} m\right) \tag{1}$$

where a, c, and m are positive integers, and X_{i+1} is the remainder of ax_{i+1} divided by m.

On this basis, the parameter $k_i = \mathrm{INT}(\frac{ax_i + c}{m})$ is introduced, where INT represents round numbers,

$$x_{i+1} = ax_i + c - mk_i \tag{2}$$

The uniform random number in the (0,1) interval is obtained through dividing x_{i+1} by m:

$$U_{i+1} = \frac{x_{i+1}}{m} \tag{3}$$

Next, the results are transformed according to the type of each random variable, and the random number conforming to the distribution law of the corresponding random variables is obtained.

Supposed that u_n and u_{n+1} are two uniformly distributed random numbers in the (0,1) interval, μ_x and σ_x are the mean and standard deviation of normal distribution random variables X, respectively, and

$$x_n = \sqrt{-2\ln u_n}\cos(2\pi u_{n+1})\sigma_x + \mu_x \tag{4}$$

or

$$x_n = \sqrt{-2\ln u_n}\sin(2\pi u_{n+1})\sigma_x + \mu_x \tag{5}$$

where x_n is a random number that obeys the normal distribution N (μ_x, σ_x).

Supposed that μ_y and σ_y are the mean and the coefficient of variation of the log-normal random variable Y, respectively, and

$$y_n = \exp\left(\begin{array}{l}\sqrt{-2\ln u_n}\cos(2\pi u_{n+1})\sqrt{\ln(1+\delta_y^2)} + \\ \ln(\frac{\mu_y}{\sqrt{1+\delta_y^2}})\end{array}\right) \tag{6}$$

where y_n is a random number that obeys the log-normal distribution.

Supposed that μ_z and σ_z are the mean and standard deviation of the random variable Z with extreme I distribution, respectively, then

$$Z_n = k - \frac{1}{\alpha}\ln(-\ln u_n) \tag{7}$$

where Z_n is a random number that obeys the extreme value I distribution, where

$$k = \mu_z - 0.57722\sqrt{6}\sigma_z / \pi \tag{8}$$

and

$$\alpha = \pi / \left(\sqrt{6}\sigma_z\right) \tag{9}$$

The random number of each random variable is substituted into the finite element equation, and then the solution of a set of variables is obtained. The distribution of the variable and the probability of failure are calculated after statistical analysis of the set of solutions.

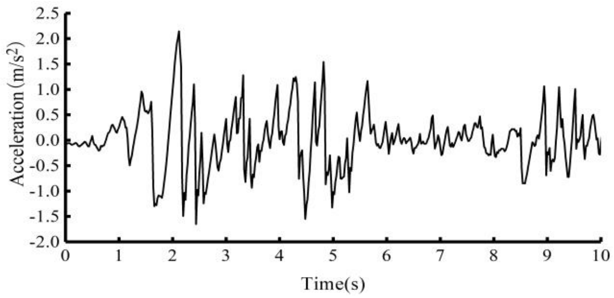
3. Seismic wave and analysis model

3.1 Seismic wave

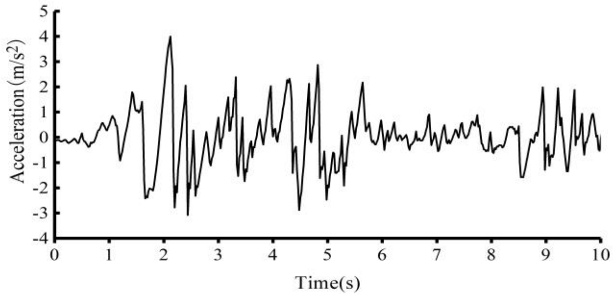
In this paper, based on the Code for seismic design of building (GB50010-2010, 2011), the El-Centro wave is selected as the seismic load to perform time history analysis of CRLSSs. In this paper, the seismic wave record of 10 s is applied in the finite element model of X direction; the seismic wave curve is shown in Fig. 1.

3.2 Analysis model

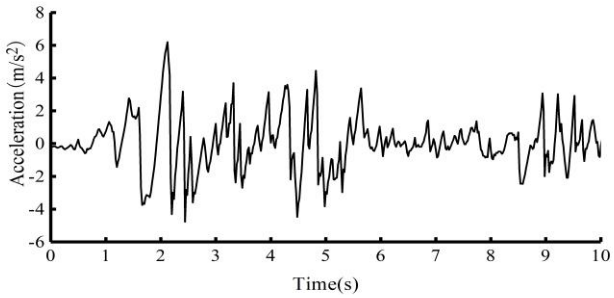
In this paper, the tensile strength of concrete is used as a reliable indicator (GB50010-2010, 2011), and the over-ground and buried CRLSSs are established by FEM. The geometry of CRLSSs are 10m×6m×4m, where the thickness of the side wall and the bottom wall of CRLSSs are 0.2m, the buried depth of the buried CRLSSs is 4m. The geometry of the CRLSSs are shown in Fig. 2.



(a) Rare fortification intensity 7



(b) Rare fortification intensity 8



(c) Rare fortification intensity 9

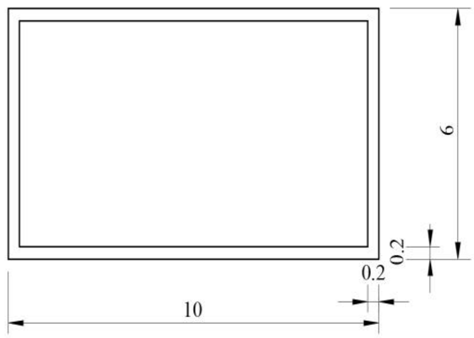
Fig. 1. Time history curve of seismic wave acceleration

Table 1 Material parameter

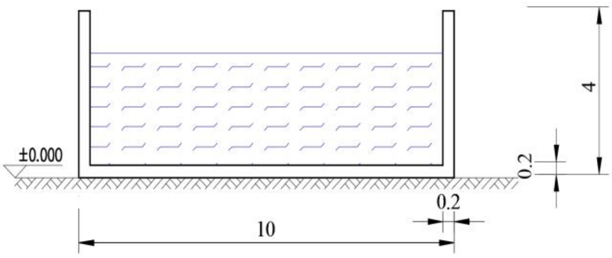
Project	Concrete	Fluid
Elastic or Bulk modulus (Pa)	3.00E+10	2.30E+9
Density (kg/m^3)	2500	1000
Poisson ratio	0.167	

The concrete material is adopted isotropic material constitutive model, and the liquid is adopted material constitutive model based on potential fluid. The structures are modeled using three-dimension solid element, and the fluid is modeled using three-dimension potential fluid element. The material parameters of CRLSS and the fluid are shown in Table 1. Considering the influences of the random wall thickness and the internal liquid depth, the seismic reliability analyses of the CRLSSs were performed under rare fortification intensities 7, 8 and 9, where the coefficient of variation is 0.25, the depth coefficient of variation is 0.3, and the structural sampling value is 200. The finite element models are shown in Fig. 3.

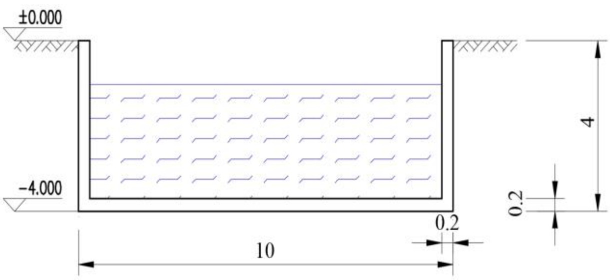
The structural boundary condition of the over-ground CRLSS is fixed at the bottom, and the structural boundary condition of the buried CRLSS is infinite boundary condition which is simulated by establishing a three-dimensional viscoelastic artificial boundary with the finite



(a) Plan of the CRLSS

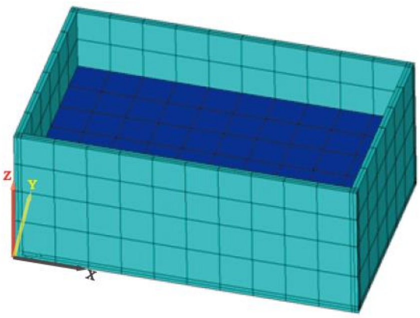


(b) Profile of the over-ground CRLSS

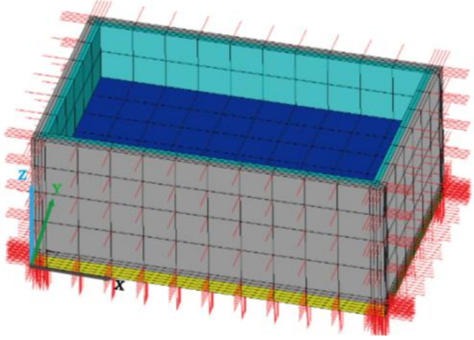


(c) Profile of the buried CRLSS

Fig. 2. Geometry of CRLSSs (m)



(a) Over-ground CRLSS



(b) Buried CRLSS

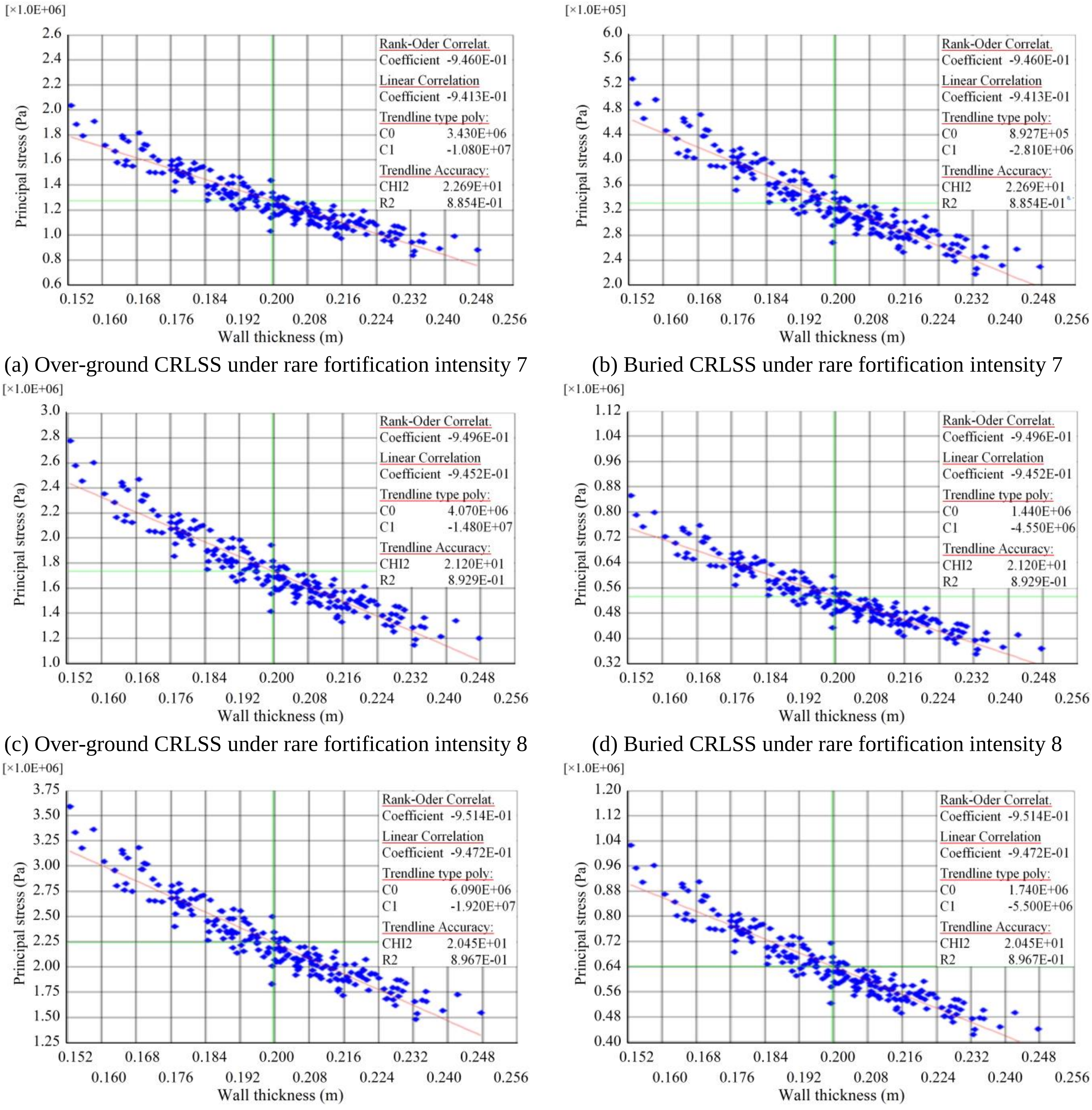
Fig. 3. Finite element models of the CRLSSs

element spring element. Two potential fluid boundary conditions, FSI boundary condition and free liquid surface boundary condition, are adopted in this paper.

The flow-condition-based interpolation FEM is used to solve the FSI system, which can obtain the relatively stable and reasonable solution of high Reynolds number flow problem under the condition of relatively rough mesh. In order to facilitate the FSI calculation, the finite element model is simplified as that (1) The liquid is an ideal fluid without viscosity, rotation, compression and heat transfer; (2) The liquid is low-amplitude sloshing; (3) The liquid surface is free.

4. Seismic reliability analysis of CRLSSs

For analysis of the seismic reliability, finding the failure mode causing the failure of the structure is critical. For a complete structural system, however, there are many uncertainties that can cause its failure, and it is impossible to consider all random variables. Therefore, multiple failure modes must be compared, with the most likely causes of structural failure taken as the standard of failure probability. Under the seismic load, the change in wall thickness is an important factor affecting the change trend of the principal stress of CRLSSs. Because the change in liquid depth leads



(a) Over-ground CRLSS under rare fortification intensity 7 (b) Buried CRLSS under rare fortification intensity 7

(c) Over-ground CRLSS under rare fortification intensity 8 (d) Buried CRLSS under rare fortification intensity 8

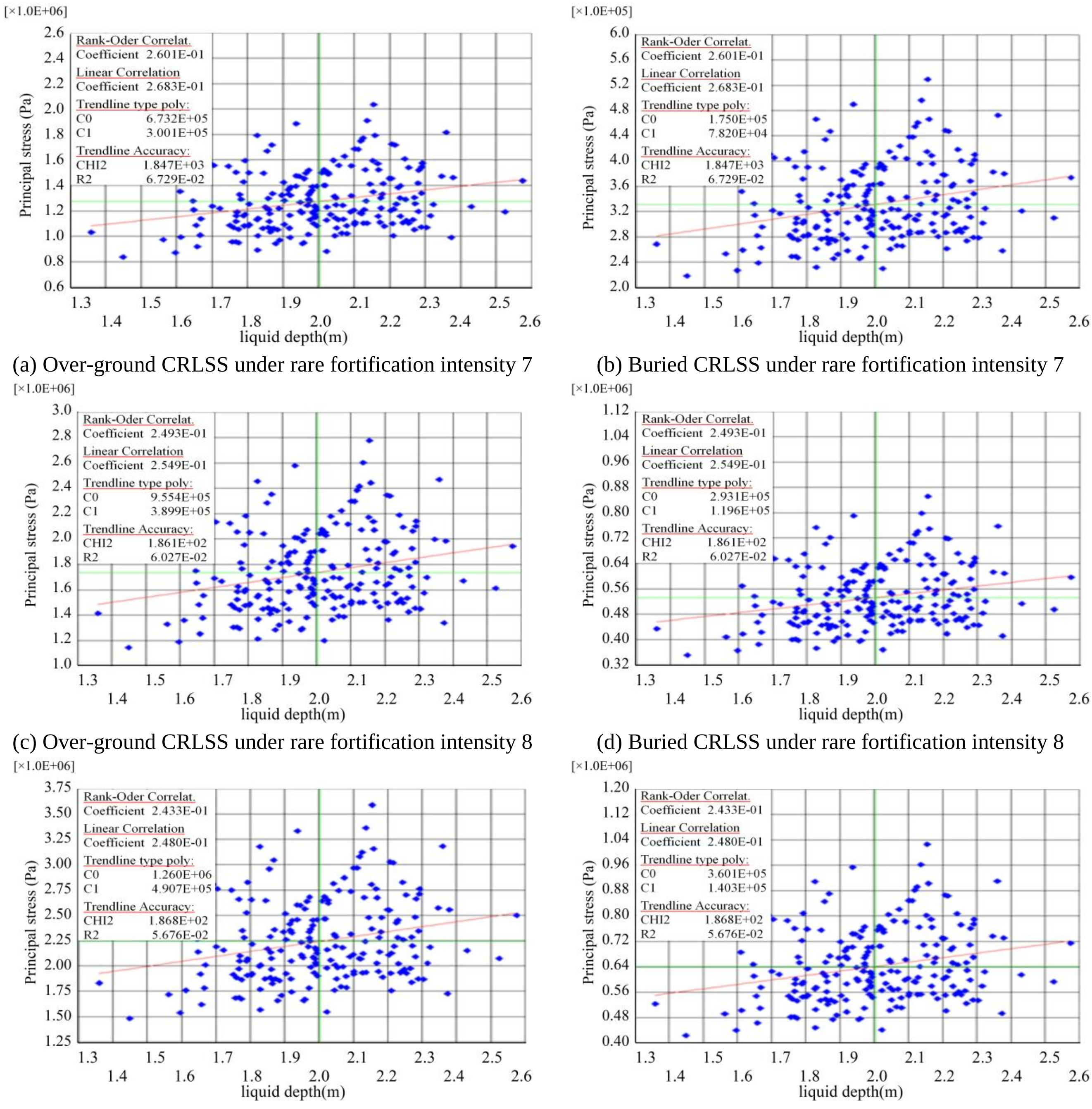
(e) Over-ground CRLSS under rare fortification intensity 9 (f) Buried CRLSS under rare fortification intensity 9

Fig. 4 Wall thickness and stress scatter diagrams of CRLSSs to the change in the liquid dynamic pressure of CRLSSs and, with the increase of the liquid depth, the weight of the liquid affects the change of principal stress of the liquid-solid coupling system of the CRLSSs, the liquid depth inside the liquid storage structure is another important factor affecting. seismic reliability. Therefore, the random change in wall thickness and the liquid depth should be considered in the seismic reliability analysis of CRLSSs.

4.1 Wall thickness

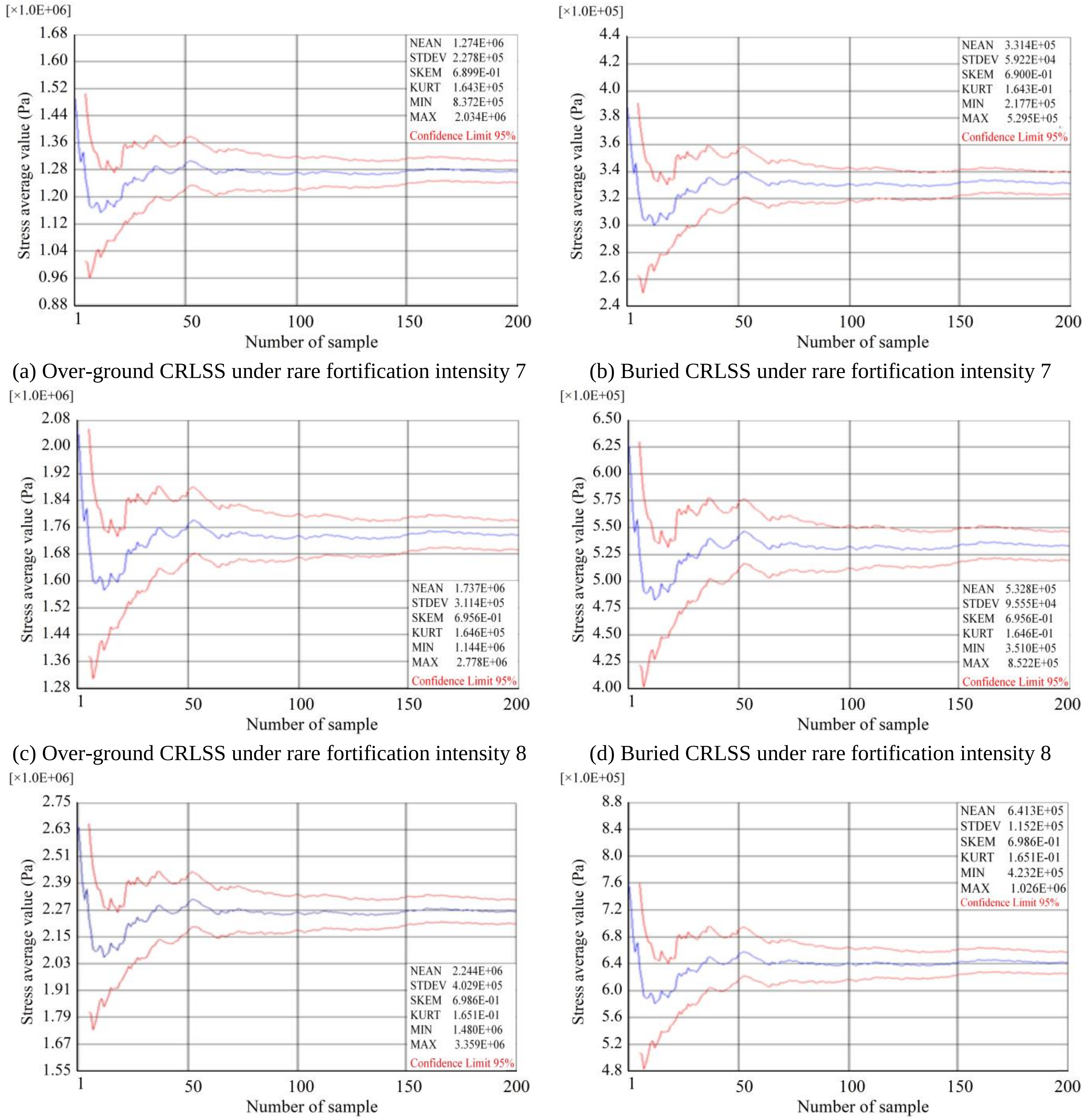
In this paper, the principal stress values of CRLSSs with different thickness are calculated based on the total number of 200 samples under rare fortification intensities 7, 8 and 9. The relationship between wall thickness and principal stress is shown in Fig. 4.

As shown in Fig. 4, with the increase of wall thickness, the principal stress of CRLSSs shows an obviously decreasing trend. The figure shows that the seismic reliability improves significantly with the increase of wall thickness and that the durability and reliability of the storage structure can be improved by properly strengthening the protection and adopting a relatively conservative design of the wall.



(a) Over-ground CRLSS under rare fortification intensity 7
(b) Buried CRLSS under rare fortification intensity 7
(c) Over-ground CRLSS under rare fortification intensity 8
(d) Buried CRLSS under rare fortification intensity 8
(e) Over-ground CRLSS under rare fortification intensity 9
(f) Buried CRLSS under rare fortification intensity 9

Fig. 5 Liquid depth and stress scatter diagrams of CRLSSs



(a) Over-ground CRLSS under rare fortification intensity 7 (b) Buried CRLSS under rare fortification intensity 7

(c) Over-ground CRLSS under rare fortification intensity 8 (d) Buried CRLSS under rare fortification intensity 8

(e) Over-ground CRLSS under rare fortification intensity 9 (f) Buried CRLSS under rare fortification intensity 9

Fig. 6 Variation curves of the stress average of CRLSSs

4.2 Liquid depth

Further analyzing and calculating the total number of 200 samples, the principal stress values of CRLSSs are calculated under rare fortification intensities 7, 8 and 9. The relationship between liquid depth and principal stress is shown in Fig. 5.

As shown in Figs. 4-5, the principal stress of CRLSSs increases with the increase of liquid depth. Compared with the change in wall thickness, the change in liquid depth has a gentler influence on the principal stress of CRLSSs. The result shows that the seismic reliability of CRLSSs is more sensitive to the change in wall thickness and that increasing wall thickness has a significant effect on improving the seismic reliability of CRLSSs.

4.3 Failure probability

The cumulative distribution function F(x) can be obtained by statistical analysis of principal stress under rare fortification intensities 7, 8 and 9. The probability at which output variable is greater than a specified limit value is

Table 2 Failure probability of CRLSSs with different strength grades under rare fortification intensity 7

Concrete strength (MPa)	30	35	40	45	50
Reliability index (N/mm^2)	2.010	2.200	2.390	2.510	2.640
Over-ground CRLSS	0.004	0.000	0.000	0.000	0.000
Buried CRLSS	0.000	0.077	0.000	0.000	0.000

Table 3 Failure probability of CRLSSs with different strength grades under rare fortification intensity 8

Concrete strength (MPa)	30	35	40	45	50
Reliability index (N/mm^2)	2.010	2.200	2.390	2.510	2.640
Over-ground CRLSS	0.207	0.077	0.037	0.016	0.007
Buried CRLSS	0.000	0.077	0.000	0.000	0.000

Table 4 Failure probability of CRLSSs with different strength grades under rare fortification intensity 9

Concrete strength (MPa)	30	35	40	45	50
Reliability index (N/mm^2)	2.010	2.200	2.390	2.510	2.640
Over-ground CRLSS	0.637	0.453	0.319	0.244	0.188
Buried CRLSS	0.000	0.077	0.000	0.000	0.000

calculated, namely, the failure probability was obtained. In this paper, the standard value of concrete tensile strength is used as the limit value. The principal stresses of CRLSSs with five different concrete strength grades are calculated, and the corresponding failure probabilities are obtained. In the whole seismic reliability analysis process, the main stress of CRLSSs fluctuates with the random variation of wall thickness and internal liquid depth. The mean value and probability distribution of principal stress vary with different seismic intensity. To intuitively understand the variation in the principal stress of structures in the whole analysis process, the curve of stress average value is shown in Fig. 6

As shown in Fig. 6, the principal stress distribution of CRLSSs changes with the increase of seismic intensity; The overall principal stress increases, with a large variation of the stress value in the initial stage, and the stress value tends to be gradually stable with the increase of the number of samples. The larger the total number of sampling is, the more accurate the calculation result of the failure probability is. In this paper, the failure probability of a CRLSSs is obtained by stress analysis of 200 samples, as shown in Tables 2-4.

As shown in Tables 2-4, the buried CRLSS has fairly high reliability. In the entire range of random factors, the structure can meet the normal use of the function and has no failure damage status. Moreover, for CRLSSs with the same strength level, the rising space of the principal stress of the structure increases, and the failure probability of the structure increases with the increase of seismic intensity. The elastic modulus of the material and the stiffness of the structure increase with the increase of concrete strength; thus, the failure probability of the structure is significantly reduced.

5. Conclusions

- According to the influences of wall thickness and internal liquid depth on the seismic reliability of CRLSSs, the reliability of the buried CRLSS under seismic load is much higher than that of the ground CRLSS.
- With the increase of wall thickness, the principal stress of CRLSSs shows an obviously decreasing trend. In other words, the seismic reliability of CRLSSs improves significantly with the increase of wall thickness.
- With the increase of liquid depth, the seismic reliability of CRLSSs decreases; However, the influence of the liquid depth change on the principal stress of the structure is relatively gentle. Therefore, the seismic reliability of CRLSSs is more sensitive to the change in wall thickness.
- With the increase of seismic intensity, the structural seismic reliability is reduced; However, the strength grade of concrete improvement can effectively improve the seismic reliability of the structure.

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