Abstract—For sandy slope, size of rock fall, groundwater level and type of site are all important factors which have significant influences on the movement characteristics of rock falls. To obtain the importance of each factor, orthogonal analysis was studied and shaking table test was drawn up. In the tests, average acceleration was chosen to be as the evaluation index, and three important factors were discussed. It is shown that size of rock fall is the main factor, the second is type of site, and the third is groundwater level. The average acceleration is the maximum when the rock fall diameter is 100mm and the groundwater level is 0.7m and the earthquake wave is T1-II-1; the minimum is when the rock fall diameter is 40mm and the groundwater level is 0.7m and the earthquake wave is T2-II-1. Analysis results provide the bombardment energy for the potential slope rock fall prevention. It is important and helpful to the protection design of structures at the foot of slope.

Keywords—sandy slope; rock falls; shaking table test; orthogonal design

I. INTRODUCTION

With rapid economic development, western region is becoming main areas of high-speed railway construction in China. However, the rail construction faces many difficult problems, such as complex terrain environment, wide cover of Aeolian sandy soil, etc. Besides western region there is a lot of sandy soil along the existed high-speed rail, especially the wetland areas. For sandy slope, the top of slope will be cut into different soil blocks when soil contacts with atmospheric, raining water, biological, physical and chemical change. Integrity of the slope is damaged and broken. The collapse of slope will happen under earthquake, which is a serious threat to the safety of the existed structures at the foot of slope.

Researchers have made a series of analysis for the collapse of rock falls both at home and abroad. Huang Runqiu[1] analyzed 6 influential factors including onset style of rolling rock, feature of overburden and vegetation, gradient of slope, length of slope, shape of rolling rock and mass of rolling rock based on site experiment of rolling rock. Zhang Guangcheng[2] studied the characteristics and influence factors of restitution coefficient of rock fall collision by the field tests. Combining with data analysis and field survey, Andrea[3] put forward the quantitative method of probabilistic risk of rock falls resulted from earthquake. Hunger[4] gave a suggestion about the reachable area range of rock fall movement according to the survey of slope collapse. Hou Tianxing[5] studied the calculation method based on impulse theorem to determine impact force of rock falls on structures.

Above all, the existed study of the slope collapse is more about mechanism of rock fall collapse, motion characteristics, field tests. There is little about various factors that influence on motion characteristics, such as seismic, groundwater level, etc. in the research. In this paper, based on different sizes of rock falls, different groundwater levels and types of sites, shaking table test was carried out to study the influence on rock fall movement of three factors.

Based on CKl62 + 075 ~ CKl63 + 075 section of Zhun-Shuo railway, the typical cutting section is studied and the type of soil is sandy soil. The slope length is 17m and slope height is 12m, as shown in Figure 1.

The size of model is determined by the size of shaking table and sand box. And the size of working plat is 1.5 square meters and the sand box is 1m(width)× 2m(length)× 1.5m(height). For the slope model, geometrical similarity coefficient is 1/24.

II. TEST SCHEME DESIGN

A. Shaking Table Test Model of Slope Rock Fall

Slope model is simulated with homogeneous and simplified model. Slope angle is 35° and slope height is 0.5m. The slope is sandy soil (clay content≥40%), and the soil is hard and is easy to condense into blocks. Rock fall diameters are 20mm, 30mm, 40mm, 50mm, 60mm, 80mm and 100mm respectively, which are used to research the influence of rock fall sizes on the collapse distance. The slope model and rock falls are shown in Figure 2. Physical parameters of slope are obtained by shear test, as shown in Table 1.
B. Test Instruments And Loading Conditions

The test is carried out on the hydraulic one-way shaking table (ES-15/KE-2000). Shaking table test consists of hydraulic control, oil pump station, and horizontal shaking table. The main technical targets of the shaking table test are as follows: maximum test load is 5000kg, maximum acceleration is 20m/s², rated speed is 0.5m/s. The size of working table is 1.5 square meters.

El Centro and different ground seismic waves (T1-II-1, T2-II-1) are chosen to analyze, as shown in Table 2. Earthquake excitations are one-way input.

| Test conditions | Type of earthquakes | Peak acceleration(g) |
|-----------------|---------------------|-----------------------|
| T01             | T1-II-1             | 0.2                   |
| T02             | T2-II-1             | 0.2                   |
| El-01           | El Centro           | 0.2                   |

C. Sensitivity Analysis of Factors

Orthogonal test design means that the typical minority are chosen from all testing schemes. Fewer tests are used to analyze testing results and find the optimal solution. Assume that A, B, C, etc. separately represent different factors, i is the level of every factor, and \( P_{ij} \) is the value of level i for factor j. The experimental result \( Q_{ij} \) can be obtained under \( P_{ij} \). \( Q_{ijk} \) (n experimental results) can be gained by n experiments under.

\[
K_{ij} = \sum_{k=1}^{n} Q_{ijk}
\]

Where \( L \) is the distance from the resting position to the foot of slope; \( N \) is the positive pressure on the ground when rock falls move on a horizontal plane; \( f \) is the rolling friction factor and can be valued as is 0.4 for the spherical rock fall based on test; \( v_0 \) is the velocity after refraction of the slope.

D. Principle of Orthogonal Test Method

Orthogonal test design means that the typical minority are chosen from all testing schemes. Fewer tests are used to analyze testing results and find the optimal solution. Assume that A, B, C, etc. separately represent different factors, i is the level of every factor, and \( P_{ij} \) is the value of level i for factor j. The experimental result \( Q_{ij} \) can be obtained under \( P_{ij} \). \( Q_{ijk} \) (n experimental results) can be gained by n experiments under.

\[
R_i = \max \{ K_{ij1}, K_{ij2}, K_{ij3}, \ldots, K_{ijn} \} - \min \{ K_{ij1}, K_{ij2}, K_{ij3}, \ldots, K_{ijn} \}
\]
E. Orthogonal Test Design

Rock fall movement is affected by many factors. It is not realistic to consider all the factors in a test. Therefore three factors are selected, including the size of rock falls, the groundwater level and the type of site as shown in Table 3.

Range of vacant column is $R_j=0.76$. The relative error is 7% which can meet the requirements.

F. Range Analysis

(1) Maximum average acceleration is No.8 test when the test combination scheme is A3B2C1. Minimum average acceleration is No.2 test when A1B2C2.

(2) Based on the shaking table test, average acceleration of rock fall can be obtained under the different combination of various factors, and the experiment results by rang analysis are analyzed, shown in Figure 5 and Figure 6. The influential order of three factors on the average acceleration is A, C and B.

IV. Conclusion

For sandy slope, it is shown that size of rock fall is the main factor, the second is type of site, and the third is groundwater level. The average acceleration is maximal when the rock fall diameter is 100mm and the groundwater level is 0.7m and the earthquake wave is T1-II-1; the average acceleration is minimal when the rock fall diameter is 40mm and the groundwater level is 0.7m and the earthquake wave is T2-II-1. With the increase of groundwater level, the distances of different diameters of rock falls show the trend of increase under different earthquakes. The collapse distance of rock fall under far field earthquake is greater than that under near field earthquake. It shows that energy of rock fall is larger and the threat is more for buildings at the foot of slope under far field earthquake.
Figure 5. Relationship between acceleration and all influence factors.

Figure 6. Range of parameters.

Table III. Factors and Levels of Orthogonal Experiment

| Levels | A(Diameter/mm) | B(Groundwater level /m) | C(Type of earthquakes) |
|--------|----------------|--------------------------|------------------------|
| 1      | 40             | 0.6                      | T1-II-1                |
| 2      | 60             | 0.7                      | T2-II-1                |
| 3      | 100            | 0.8                      | El Centro              |

Table IV. Analysis and Computation

| Test number | 1(A) | 2(B) | 3(C) | 4     | Average acceleration (m/s²) |
|-------------|------|------|------|------|----------------------------|
| 1           | 1    | 1    | 1    | 1    | 9.37                       |
| 2           | 1    | 2    | 2    | 2    | 8.61                       |
| 3           | 1    | 3    | 3    | 3    | 10.84                      |
| 4           | 2    | 1    | 2    | 3    | 11.47                      |
| 5           | 2    | 2    | 3    | 1    | 11.73                      |
| 6           | 2    | 3    | 1    | 2    | 11.78                      |
| 7           | 3    | 1    | 3    | 2    | 13.30                      |
| 8           | 3    | 2    | 1    | 3    | 13.65                      |
| 9           | 3    | 3    | 2    | 1    | 12.71                      |
|             | 28.82| 34.14| 34.80| 33.80| 103.46                     |
|             | 34.98| 33.99| 32.78| 33.69|                            |
|             | 39.67| 35.33| 35.88| 35.96|                            |
|             | 9.61 | 11.38| 11.60| 11.27|                            |

\[ \sum y_i = 103.46 \]

\[ \frac{1}{9} \sum y_i = 11.50 \]
REFERENCES

[1] Huang R, Liu W. (2009). “In-situ test study of characteristics of rolling rock blocks based on orthogonal design.” Journal of Rock Mechanics and Engineering, Vol 28(5): 882-891.

[2] Zhang G, Xiang X, Tang H. (2011). “Field test and numerical calculation of restitution coefficient of rockfall collision.” Journal of Rock Mechanics and Engineering, Vol 30(6): 1266-1273.

[3] Valagussa A, Frattini P, Crosta G B. (2014). “Earthquake-induced rockfall hazard zoning.” Engineering Geology, Vol 182(2014): 213-225.

[4] Hungr O D, Evans S G. (1988). “Engineering evaluation of fragmental rockfall hazards.” Proceedings of the 5th International Symposium on Landslides and Engineered Slopes, 685-690.

[5] Hou T, Yang X, Huang C, et al. (1988). “A calculation method based on impulse theorem to determine impact force of rockfall on structure.” Journal of Rock Mechanics and Engineering, Vol 34(Supp.1): 3116-3122.