Collapse behavior simulation of cylindrical steel shell under landslide impact

Menghong Wang¹, Feiyu Shi¹,*, Yaoxiang Zhao¹ and Xiaobin Zheng¹

¹School of civil and transportation engineering, Beijing university of civil engineering and architecture, 100044, Beijing.

*Email:2108140218002@stu.bucea.edu.cn

Abstract. ANSYS/LS-DYNA dynamic analysis software was adopted to establish a model of a grid structure impacted by a landslide load, with the dynamic effects of impact loads and contact collision theory considered based on Hamilton’s principle. The case analysis in this study can provide guidance for anti-slump design in similar projects.

1. Introduction
Space grids are widely used for public large-span space structures such as airports, stations, and stadiums. In recent years, owing to the environmental protection requirements, a large number of storage silo structures have been used in power plants, steel mills, and cement plants, with spans reaching 150 m or more. Because these large-span storage silos are often located in factory areas, structural collapse often occurs under the action of strong winds, heavy snow, or strong earthquakes which exceed the design specifications. Local collapse and total failure of these structures caused by landslides also occur occasionally.

The ANSYS/LS-DYNA dynamic analysis software is used to simulate the collapse behavior of grid structures under unconventional design loads such as explosions, missiles, landslides, and rockfalls. It is necessary to apply dynamic analysis, basic contact collision theory, and geometric and material nonlinearity comprehensively to predict the possible collapse of the structure more accurately. This study is focused on improving design collapse resistance through local strengthening to prevent problems proactively. Most previous studies [1-6] have focused on single point impacts on single-layer reticulated shells, but there are few studies simulating the effects of large-scale landslides.

This study investigates the partial collapse of a grid structure caused by a landslide, and a model of an actual grid is simulated during the impact of a landslide. Based on the energy change and dynamic response of the structure, the failure mode of the structure resulting from landslide damage is discussed in detail.

2. Basic theory of impact dynamics

2.1. Establishment and solution of the dynamic equilibrium equation
The analysis of structural dynamics requires establishment of structural dynamic equilibrium equations based on the structure of interest and the loads applied. A reasonable solution method must then be applied for the numerical calculation. The most common method for establishing the dynamic equilibrium equation uses D’Alembert’s principle to balance the equation directly, but this method is not suitable for complex structures. For complex structures, the motion equation can be established
using the virtual displacement principle, but only vector addition can be permitted. By applying Hamilton’s principle to establish the equation of motion, the disadvantages of D’Alembert’s principle and the virtual displacement principle can be avoided. Hamilton’s principle is expressed as Eq. (1).

$$\delta J_H = \delta \int_{t_i}^{t_f} L \, dt = \delta \int_{t_i}^{t_f} (T - V) \, dt + \delta \int_{t_i}^{t_f} W_n \, dt = 0$$  \hspace{1cm} (1)

where $J_H$ is the Hamilton effect; $L$ is the Lagrange function; $T$ is the total kinetic energy, $T = m \dot{u}^2 / 2$; $V$ is energy of position, $V = Ku^2 / 2$; $W_n$ is the work of non-conservative forces on the system; and $\delta$ is the variation within the specified time period.

Hamilton’s principle can be described as follows: in any time period, the sum of the variation in the kinetic energy and energy of position plus the non-conservative force is always zero. The Hamilton principle differs from the virtual work method in that it uses variations in the kinetic energy and potential energy instead of the inertial force and elastic force. The equation established with this method is only related to the scalar energy, and is therefore more applicable to situations in which an impact load acts on the structure [7].

The explicit center difference method used in ANSYS/LS-DYNA represents the speed and acceleration in the equation of motion by different combinations of displacements, which converts the hard-to-solve differential equations into algebraic equations that can easily be solved numerically, and derives the recurrence formula for each time step. The structural reaction during the entire exercise can then be obtained. Thus, this study uses the explicit center difference method to solve the equation.

### 2.2. Dynamic constitutive model of the materials

Cowper-Symonds constitutive equation was employed to consider the effect of the material strain rate. The equation (2) expresses the relationship between the strain rate and the flow stress; the temperature factor is not included, and only the influence of the strain rate is considered [8].

$$\sigma_y = \left[\sigma_0 + f_h(\dot{\varepsilon}_p^{\text{eff}})\right] \left(1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{\frac{1}{P}}\right)$$  \hspace{1cm} (2)

where $\sigma_y$ is the yield stress, $\dot{\varepsilon}^{\text{eff}}$ is the effective strain rate, $C, P$ are strain rate parameters, and $f_h(\varepsilon_p^{\text{eff}})$ is the hardening function for the effective plastic strain.

### 2.3. Basic theory of contact and collision

Common contact algorithms include the dynamic constraint method, distribution parameter method, and penalty function method. The penalty function method is used as the contact algorithm in this study. The basic principle of the penalty function method is to check the boundaries of each major surface for each $\Delta t$ to determine if the boundary has been penetrated from the node. If not, processing is performed. Otherwise, a contact force is exerted on the interface, which can be calculated according to Eq. (3), and is equivalent to adding a series of springs between the interfaces.

$$F = k \delta$$  \hspace{1cm} (3)

Where, $k$ is the contact surface stiffness, and $\delta$ is the contact surface penetration.

### 3. Treatment of landslide impact

Simulation of an actual landslide is relatively complicated and requires consideration of many factors. Because the primary impact material in the landslide in this case is mountain gravel and the actual amount of earthwork is small, the treatment can be simplified as stones impacting the grid. When the grid is impacted by stones, the stones at the lower grid structure are larger and more numerous, while the stones at higher locations are lighter and less abundant. Therefore, the following assumptions are made:

1) The mass of the stones decreases linearly from the bottom to the top of the structure, with an equilateral triangle distribution;
2) The site of the impact by the stone occurs at the node of the grid;
3) The stones are not broken and are spherical in shape.

4. Grid finite element model
This study uses an actual structure as the analysis model, and this structure has a span of 50 m × 248 m, a height of 20.438 m, and an unfolded area of 19,880 m². The perimeter of the grid is fixed by a three-way hinged support.

Based on the symmetry of the grid structure, 1/2 of the overall structure is used for the simulation. The grid bars are modeled using beam element BEAM161. For the bars, a piecewise linear plastic material model was used, with a yield strength of 207 MPa, elastic modulus of 206 GPa, and Poisson's ratio of 0.3. The landslide impact material was simulated using the solid element SOLID164. To facilitate modification of the parameters, the impact material was defined as a sphere with a radius of 0.62 m and volume of 1 m³. The roof dead load and bolt ball weight were simulated using MASS166.

![Figure 1. Views of the structural model.](image)

The initial position of the landslide impactor is in the positive y-direction from the impacted node. The change in weight of the landslide is achieved by varying the material density of the impact material, and the density of the lower impact material is greater than the density of the upper impact material. The landslide impact grid is realized by impacting the grid from a horizontal direction with a certain initial velocity. The model is shown in Figure 1.

5. Structural dynamic response
The failure modes can be divided into three situations: 1) slight damage leading to a dent (less than 0.5% of the bars in the impact area); 2) failure of a large number of bars in the impact area (less than 0.5% of bars in the impact area); and 3) overall structure failure with a large number of bar failures (the overall structure is greater than 0.5% of the bar failure).

The simulation results show that Mode 2 is more similar to the results of an actual landslide. A lower monomer mass of 1500 kg, upper monomer mass of 750 kg, and impact velocity of 50 m/s. The impact process is shown in Figure 2. After the simulated impact object collides with the grid, the nodes in the impact area move horizontally together. The neighboring nodes around the impact area also move horizontally along with the impact area.

When the displacement of the horizontal movement reaches a maximum, some of the impact objects rebound, and the grid will vibrate and consume energy to reach a certain equilibrium position. This process is accompanied by the failure of some of the bars. Eventually, a few bars in the impact area of the grid will fail.

![Figure 2. Impact process.](image)
5.1. Kinetic and strain energy of the grid
The kinetic energy history curve for the grid is shown in Figure 3. Immediately after the grid node is impacted, the kinetic energy of the grid increases.

![Figure 3. Grid energy time history.](image)

At 0.009 s, the kinetic energy reaches a maximum value of $2.4 \times 10^6$ J, after which the kinetic energy decreases rapidly, and the kinetic energy is quickly transformed into strain energy in the grid. After 0.2 s, the kinetic energy of the grid is relatively small, i.e., almost zero, indicating that the kinetic energy of the grid has been converted into strain energy.

At 0.1 s, the strain energy of the grid increases to $1.83 \times 10^7$ J. After 0.4 s, the strain energy of the grid begins to decrease stepwise. At 0.11 s, 0.14 s, 0.15 s, 0.32 s, and 0.469 s, the strain energy of the grid undergoes a sudden change. Finally, the strain energy of the grid stabilizes at $1.54 \times 10^7$ J. This is because at each of the above five moments, one bar member reaches the maximum plastic strain, which causes it to lose its ability for load bearing, and a portion of the energy is consumed.

The total kinetic energy time history of the grid is shown in Figure 4. The kinetic energy increases again at 0.24 s. This is because the impact area of the grid begins to rebound after the horizontal displacement reaches its maximum value, and the grid vibrates around the equilibrium position.

5.2. Node y-direction velocity
The lower layer is impacted at node 3454, and the upper layer is impacted at node 3453. Nodes 3456 and 3458 are laterally adjacent to the impact point. When the impact object contacts the grid, the velocity of the impacted node increases sharply. The velocity of node 3454 reaches -52.0 m/s within 1 ms, while node 3453 reaches -18.1 m/s. As the impact loading ends, the velocity at the impact point no longer increases. Furthermore, the speed decreases rapidly due to the need to drive the horizontal movement of neighboring nodes. The duration of the impact is very short. At this time, the velocity development at adjacent nodes 3456 and 3458 is delayed, and the fluctuation is not severe. Driven by nodes 3454 and 3453, the velocities of adjacent nodes 3456 and 3458 increase continuously, and the y-direction velocities of the nodes all gradually decrease toward zero. The node velocity variation at each corresponding position is basically the same as the y-direction velocity variation observed for the impacted node and adjacent nodes in the third column.

5.3. Node y-direction displacement
The y-direction displacements for the impacted nodes and adjacent nodes in the third column are shown in Figure 5(a). At the moment of impact, the displacement at the impacted point increases sharply. Within 60 ms, the y-direction displacement of node 3454 reaches -0.902 m, and the displacement of node 3454 reaches -0.779 m. Because the impact duration is extremely short, the displacements of adjacent nodes 3456 and 3458 are delayed. Driven by nodes 3454 and 3453, the displacements of adjacent nodes 3456 and 3458 increase continuously, and the displacements of adjacent nodes 3456 and 3458 continuously increase, and the displacements of the nodes in the y-direction then all gradually decrease and tend to stabilize. During the entire impact process, the time of maximum displacement increases sequentially from the bottom up to the four nodes in turn, which is consistent with the change in an actual impact.
The y-direction displacements for the impacted nodes and adjacent nodes in the sixth column are shown in Figure 5(b). The change in the node displacement at each corresponding position is basically the same as the y-direction displacements observed for the impact and adjacent nodes in the third column.

5.4. Stress of the bars

The stress time history curve for bars at the impact position in the third column and an adjacent bar are shown in Figure 6(a). The compressive stress of bar 2410 is 622 MPa at 0.053 s. The tensile stress of bar 2411 is 267 MPa at 0.015 s. The tensile stress of bar 2412 is 366 MPa at 0.031 s. The tensile stress of bar 2413 is 345 MPa at 0.041 s. The instantaneous stresses of these bars are much greater than the yield strength of the steel under a static load, indicating that the strain rate effect has a significant influence on the structure of the grid under an impact load. The bar will continue to oscillate after the impact force ends.

The stress time history curve for bars at the impacted position in the sixth column and adjacent bars is shown in Figure 6(b). The stress time history curve of the axial stress for the bars in each corresponding position is basically the same as that observed for the impact position in the third column.

5.5. Plastic development and plastic area of the grid structure

For the development of plastic strain in the impact process, Figure 7(a-c) shows that with the development of the impact process, most of the bars around the impact area enter plasticity. In this simulation, only a few bars failed. Most of the other bars entered the plastic stage. A bar entering plastic strain is deemed a damaged bar.
The distribution of bars entering plasticity is shown in Figure 8. Red bars indicate the occurrence of plastic strain. Most of the bars in the impact area enter the plastic stage. There are also a few bars in the non-impact area which enter the plastic stage. The plastic bars in the non-impact area mostly occur near the transverse upper and lower chords.

Figure 7. Plastic strain development during impact.

Figure 8. Distribution of plastic bars (shown in red).

Figure 9. Comparison of actual grid damage and simulation results.

A comparison of the actual grid damage with the simulation results is shown in Figure 9. It can be seen that the simulation results in this study are roughly the same as the damage to the grid after the actual landslide impact.

5.6. Strengthening of key bars

Based on the above analysis, the key bars in the grid under an impact load are the bars that enter the plastic stage in this mode, i.e., the red bars in Figure 8. This study replaces the plastic bar members with Q345 members to increase their yield strength and thus achieve the effect of grid strengthening [9].

Figure 10. Distribution of reinforced plastic bars (shown in red).

The relevant analysis of the dynamic response discussed above is performed on the grids after strengthening the identified key bars. The same impact load is applied in the analysis. The resulting distribution of grid bars entering the plastic stage is shown in Figure 10. In the impact area, some of the bars entered plasticity, while only a very small number of bars in the non-impact area entered the plastic stage. After strengthening, the number of bars entering the plastic stage has been greatly reduced, and the failure mode has changed from Mode 2 to Mode 1.

The dynamic response of the strengthened grid under different impact masses and velocities was analyzed by changing the mass and velocity parameters of the impact material. After reinforcement,
the failure mode of the grid is improved compared with the ability of the unreinforced grid to resist collapse.

After strengthening the key bars, under the same impact load, the number of bars entering the plastic stage is reduced significantly, and the structure is more resistant to collapse. The results also demonstrate that the reinforced design for key bars can enhance the collapse resistance of the structure under an impact load.

6. Conclusions
1) With increasing impact energy, the sequential failure modes of the double-layer cylindrical lattice are slight damage to the depression, failure of a large number of bars in the impact area, and failure of a large number of bars in the overall structure. The simulation results show that Mode 2 is consistent with the impact on a grid by an actual landslide.

2) Most of the bars around the impact area enter plasticity. The distribution of plastic bars shows that the plastic development of the structure does not extend to the entire grid. The grid bars in the non-impact area which enter plasticity are mostly located in the transverse upper and lower chords.

3) When the grid is impacted by a landslide, the impact area is impacted and gradually expands. The kinetic energy is then absorbed by the grid and decreases. Finally, the kinetic energy is almost completely converted into strain energy. The strain energy continues to increase and eventually stabilizes.

4) The stress of the bars under impact loading can be much greater than the yield stress under static loading. The steel material is thus a strain rate sensitive material. Whether or not the strain rate effect is considered in the structural analysis under impact loading can affect the results.

5) The key bars of the double-layer grid structure are determined under the impact load. By strengthening the design of the key bars, the collapse resistance of the structure under impact loading can be effectively enhanced. In addition, this method for improving the ability of the structure to resist collapse can also be used as guidance for related projects.

Acknowledgement
This study is sponsored by the BUCEA Post Graduate Innovation Project(PG2020029).

References
[1] Guo Ke 2004 Dynamic analysis of single-layer reticulated shells under impact [D]. Taiyuan: Taiyuan University of Technology
[2] Wang Duozhi 2010 Failure mechanism of reticulated shells under impact [D]. Harbin: Harbin Institute of Technology
[3] Fan Feng, Wang Duozhi, Zhi Xudong, et al 2009 Performance for kiewite8 single-layer reticulated domes subjected to impact load Engineering mechanics 26 (06)75-81
[4] Fan Feng, Wang Duozhi, Zhi Xudong, et al 2010 Failure modes and discrimination method for Kiewitt reticulated dome under impact loads China civil engineering journal 43 (05)56-62.
[5] Shi Junliang 2005 Dynamic response research on K8 single-layer reticulated dome under impact [D]. Taiyuan: Taiyuan University of Technology
[6] Tian Yonghong 2010 Failure modes of geodesic and schwedler reticulated domes under impact loads [D]. Harbin Institute of Technology
[7] Ray Clough, Joeshp Penzien, Wang Guangyuan, et al. Dynamics of structures (Revised Edition) [M]. Beijing: Higher education press 2006 7
[8] LSTC. LS-DYNA 2015 keyword user’s manual[M]. California: Livermore Software Technology Corporation
[9] Xiong Mingxiang 2005 Study on impact response and protective measures of steel structure with composite slab under impact loads [D]. Wuhan: Huazhong University of Science and Technology