Impact response of reinforced concrete slabs in elastic half space

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Abstract: The analysis of the mechanical behaviour of reinforced concrete slabs on elastic foundation under impact loads is of great significance in the construction and protection of concrete pavements in airports. Based on the Elastic Half-space Foundation Model and Concrete Damage Plasticity Model, the displacement and stress fields of reinforced concrete slabs under impact loading are numerically simulated by explicit nonlinear finite element method. The result can be used to design and evaluate the safety of foundations and reinforced concrete slabs under impact loads.

1. Introduction
The problem of contact between the foundation and foundation of the structure has always been an important area of engineering mechanics research. The foundation and foundation of the structure are a whole, and the interaction force and associated displacement will occur at the junction of the two under load. If the foundation is regarded as an elastic thin plate, the problem of contact between the foundation and the foundation becomes a problem of contact between the thin plate and the foundation. Many practical engineering problems, such as building raft foundations, highways, airport runways, power plant foundations and so on can be considered as contact problems between the thin plate and the foundation. At present, the civil aviation airport pavement mainly adopts the concrete rigid pavement with strong vertical impact load capacity. And the design of airport pavement concrete slab mainly adopts the empirical design method based on specification[1]. The load calculation of concrete slab is carried out by using the empirical formula (1).

\[ P = \frac{Gp}{n_c n_w} \]

In the formula, \( P \) is the wheel load on the main landing gear (kN); \( G \) is the weight of the aircraft; \( P \) is the load distribution coefficient of the main landing gear; \( n_c, n_w \) are the number of the main landing gear and the number of wheels on each landing gear. In the formula (1), the vertical impact of the load is not considered. Although the service life of concrete slabs on airport pavement is 30 years, the concrete defects on airport pavement will occur when the service life is often not reached. The possible reason for this phenomenon is that the impact load when the aircraft is landing is not fully considered in the design calculation. Taking a Boeing 767 aircraft as an example, its empty load is 80 tons and the minimum drop speed is 200km/h. The impact load generated during landing is huge.
Based on this, this paper uses the ABAQUS-based display dynamics analysis technology to analyse the Mises equivalent stress field, equivalent plastic strain (PEEQ) and the settlement law of elastic foundation of cement concrete pavement on elastic foundation under impact load.

2. Mechanical model for interaction between foundation and foundation plate
The foundation soil medium is a three-phase discrete system of solid, liquid and gas. The mechanical behaviour under load is nonlinear, irreversible and time-varying in physical relationship, and has obvious anisotropy and non-uniformity. When analysing the contact problem between soil and foundation, it is difficult to consider all the characteristics of foundation soil [2]. Therefore, some approximate foundation soil models have to be used instead of real soil media. At present, linear elastic foundation models include Winkler foundation model [3] [4], two-parameter foundation model [5] and elastic half-space model[6] [7] are widely used. The elastic half-space model assumes that the foundation is an isotropic, uniform, elastic semi-infinite body, and the elastic modulus is $E_s$, Poisson's ratio is $\mu$; J. Boussines (1892) deduced the displacement distribution of an elastic half-space surface subjected to a concentrated vertical load (eq. 2), which laid a foundation for the application of the elastic half-space model in the calculation of soil-foundation interaction problems.

$$w(r,0) = \frac{P}{4\pi G_s} \left(1 - \mu_s\right) \frac{1}{r}$$

In the formula: $r$ is the distance from the load point of the elastic half space to the displacement point.

3. Plastic damage model of concrete
The plastic damage model of concrete is the development and revision of the widely used Drucker-Prager strength criterion. The model considers that the main failure mechanism of concrete is tensile cracking and compressive fracture of concrete materials[8][9]. This model describes the irreversible damage during crushing or cracking by using non-associated hardening plastic strain and isotropic damage variables. The yield surface equation, stress-strain relationship and damage evolution variable are used to describe the model which takes into account the stiffness recovery effect under cyclic loading and can be used to analyse the dynamic response of reinforced concrete structures under impact loading.

$$\bar{q} = \sqrt{\frac{1}{2}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)}$$

The CDP model considers that the plastic flow of concrete is non-correlative and tension-compression anisotropic. Hyperbola function is used to describe the characteristics of yield surface. And the rule of flow is:

$$\sigma = (1-d)D^0_e : (\varepsilon - \varepsilon_p)$$

$$F = \frac{1}{1-\alpha} \left(\bar{q} - 3\alpha \bar{p} + \beta(\delta_p)/(\delta_{\text{max}}) - \gamma(\sigma_{\text{max}}) - \bar{\delta}_{\text{p}}\right) = 0$$

$$G = \sqrt{(\varepsilon \sigma_{\text{lo}} \tan \psi)^2 + \bar{q}^2 - \bar{p} \tan \psi}$$

In the formula, $\sigma$ is the stress tensor; $D^0_e$ is the initial elastic matrix; $d$ is the damage parameter; $\alpha, \beta, \gamma$ are the yield surface parameter; $\bar{p}$ is the equivalent hydrostatic stress, $\varepsilon$ is the eccentricity coefficient and $\psi$ is the expansion angle.

It is assumed that the main two concrete failure mechanisms are the tensile cracking and compression crushing of the concrete material. The CDP model can analyse concrete structures under monotonic, cyclic, and dynamic loading [4]. It takes into account stiffness recovery effects in cyclic loading[10][11].
The evolutions of the damage components $d_c$ and $d_t$ are linked to the corresponding plastic strain. It is determined proportional to the inelastic strain using a constant factor\(^{[12]}\), which both are experimentally determined. (Fig.1)

![Damage Evolution in CDP model](image)

Fig.1 Damage Evolution in CDP model

4. **Numerical analysis**

4.1. **Finite element modeling and analysis**

In this paper, the stress and deformation of reinforced concrete slabs on elastic foundation with four free edges under impact loading are analysed. The reinforced concrete slab is 4 m in length (x-axis), 3 m in width (y-axis), 0.4 m in thickness and 2400 kg/m\(^3\) in density. The elastic modulus of reinforcing bar is 210 GPa, and poisson's ratio is 0.27. The foundation slab is equipped with double-deck bidirectional reinforcing bar according to 16@200, and the erected reinforcing bar is A10. The yield strength of reinforcing bar is 400 MPa. On the basis of testing and measuring the strength index of C40 concrete and according to CEB-MC1990 code, the calculation parameters of concrete plastic damage model are shown in Table 1.

| Modulus of elasticity | Possion’s ratio | Density | Mean value of compressive strength | Mean value of tensile strength | Tensile strain for Mean value of compressive strength | Tensile strain for Mean value of tensile strength |
|-----------------------|----------------|---------|-----------------------------------|-------------------------------|-----------------------------------------------------|---------------------------------------------------|
| $E$                    | $\nu$          | $\rho$  | $f_{cm}$                          | $f_{ctm}$                     | $\varepsilon_{cm}$                                  | $\varepsilon_{ctm}$                                |
| $3.6 \times 10^4$ MPa | 0.2            | 2400 kg/m\(^3\) | 3.5 MPa                          | 48 MPa                        | $1.5 \times 10^{-4}$                               | $2.2 \times 10^{-5}$                                 |

The elastic foundation has an elastic modulus of 35.0 MPa, a Poisson's ratio of 0.32, and a density of 1500 kg/m\(^3\). The displacement and stress distribution of the foundation with a diameter of 8 m and a depth of 6 m are calculated. The horizontal displacement around the foundation is constrained, and the displacement along the bottom boundary is constrained in three directions. The impact mass of 1254 kg acts on a circular area with a central diameter of 0.8 m. The impact energy and velocity are shown in Table 2.

| energy/J | $v/(m \cdot s^{-1})$ | $h/m$ | $m/kg$ |
|----------|-----------------------|-------|--------|
| 6143     | 3.13                  | 0.5   | 1254   |
| 12305    | 4.43                  | 1     | 1254   |
| 24571    | 6.26                  | 2     | 1254   |

4.2. **Stress and strain analysis of reinforced concrete slab**

Figure 2 shows the Mises equivalent stress cloud and the equivalent plastic strain cloud diagram of the concrete slab under the three different impact loads shown in Table 1. Figure 2 shows that with the
increase of impact energy, the maximum Mises equivalent stress increases from 14.2 MPa, 21.5 MPa to 21.8 MPa. A comparison of the figure (a), (b) and (c) shows that as the impact energy increases, the influence range of the plate equivalent stress peak region is expanded. The equivalent plastic strain peaks are $2.57 \times 10^{-4}$, $4.56 \times 10^{-4}$, $1.04 \times 10^{-3}$, respectively. Figure (g), (h), (i) reflects that the equivalent plastic strain is mainly caused by the impact of the center of the plate within the "volcano" type area.

![Fig.2 Mises equivalent stress nephogram of the top and bottom of orthogonal anisotropic plates](image)

Figure 3, Figure 4 and Figure 5 show the maximum tensile stress and maximum compressive stress cloud diagram of the steel bars in the reinforced concrete slab under different impact loads. During the impact, the bottom steel bar is pulled and the top steel bar is pressed. The vertical erected steel bars near the impact zone are mainly subjected to tensile stress, which indicates that the erected steel bars can play a role of “transmitting rods” that transmit the impact load on the top of the plate to the foundation to a certain extent. The load transferring mode of erected steel bar is bending deformation of slab and foundation system, which leads to vertical erected steel bar being stretched downward, instead of stress transferring directly to slab and foundation.
Fig. 5 shows the attenuation law of vertical displacement (U3) of reinforced concrete slab and foundation with the impact load in depth and horizontal direction, respectively. The figure reveals that the displacement of the bottom of the reinforced concrete slab is smaller than the corresponding position of the elastic foundation, and the difference is about 2-5 mm. Because the stiffness of the plate is much larger than the stiffness of the foundation, the central region of the plate will be disengaged from the foundation under impact loading. Figure (a) shows the displacement of the impact load on different depths of the foundation, indicating that in the depth region of the 1m foundation, the settlement value is small and the curve tends to be gentle. Figure (ba) shows the displacement of the impact load on the surface of the foundation at different locations, indicating that the settlement is getting smaller and smaller as the impact position is getting farther and farther. The settlement curve tends to be gentle at 1.5m from the impact region.
Fig.5 Profile of impact load and settlement of reinforced concrete plate-elastic foundation

5. Conclusions

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used. In this paper, the explicit finite element method is used to analyze the stress and displacement fields of reinforced concrete slabs on elastic foundation under impact loading. Combined with the actual situation of engineering design, the foundation adopts the elastic half-space foundation model, the concrete adopts the plastic damage model and the mechanical parameters of the concrete are determined. Conclusion is as follows:

(1) The reinforced concrete slab has better tensile and impact resistance than the concrete slab. The steel reinforced concrete frame in the concrete slab also bears part of the tensile stress caused by the impact load while restraining the concrete. At the same time, the standing steel bars in the board can play the role of “transmitting rod”.

(2) In the area of the impact load, the concrete slab has a pit-like deformation, which is caused by the compression plastic deformation of the concrete.

(3) The calculation shows that the settlement in the elastic foundation mainly occurs in the limited area at the bottom of the reinforced concrete slab. During the design and construction, it can be considered that the displacement caused by the impact load is small in the foundation far from the impact position. This has certain practical significance for the design and calculation of similar airport runway foundations and foundations.

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