Numerical Simulation of Thermal Coupling Process of Foundation Pit under Freezing and Thawing

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Abstract—The excavation depth of foundation pits in modern urban high-rise buildings and underground engineering is getting larger and deeper, and the shape of the foundation pits is more complicated due to the surrounding environment. At the same time, the foundation pit construction in seasonal frozen soil areas is still facing the freezing and thawing effect during winter. It affects the stress and deformation deformation of the foundation pit and the supporting structure, and even cause the foundation pit to be unstable. Thermodynamic coupling numerical analysis model considering the influence of freezing and thawing in the background of the second stage foundation pit engineering of Shenyang Dongsen CBD Business Plaza was established in the paper, through the controls of temperature parameter to simulate the temperature change process under different working conditions, revealing the temperature effects on the foundation pit and the internal force and deformation law of the foundation pit. It has certain application value and reference significance for guiding the practice of foundation pit engineering in seasonal frozen soil areas.

Keywords—foundation pit; freeze-thaw action; thermo-mechanical coupling; numerical simulation; seasonal frozen soil

I. Introduction

China's permafrost regions and seasonal permafrost regions are the third largest in the world [1]. In the construction of frozen soil areas, various freeze-thaw disasters are formed during the short-term freezing and freezing period, which endangers the safety and use of various projects and causes huge economic losses. In the construction of deep foundation pits in seasonally frozen soil areas, the influence of soil frost heave on foundation pits is often neglected. At present, the freezing and thawing problems are not considered in the design of foundation pit support structures, so the necessary Corresponding anti-freezing measures leave a safety hazard to the foundation pit support project. Scholars from all over the world have conducted a lot of research on the temperature field and thermodynamic coupling model of frozen soil. After the 1980s, the Frozen Soil Institute of the world's advanced cold regions countries used the achievements of other disciplines to further promote the development of research in the field of temperature fields. It is mainly to establish and solve the theoretical model of multi-dimensional multiphase nonlinear problems and multi-field interaction problems. In the 1990s, the Chang'an University Frozen Soil Research Group proposed a method for solving the temperature field of frozen soil roadbed by finite element method under consideration of various factors. Based on the Harlan fluid dynamics model,

Shen Mu [2] established a quasi-three-field coupling model; Zhang Lixin [3] and other computerized tomography scanners combined with the characteristics of the water field before and after the actual test, analyzed the closed system. Dynamic coupling process of frozen soil in water field and density field under temperature gradient. He Ping [4] proposed three coupling equations in the process of soil freezing. Wang Tiexing [5] proposed a hydrothermal coupling calculation model for frozen soil subgrade, and gave a general flow chart for hydrothermal coupling calculation. Li Hongsheng [6] proposed a general mathematical model for the coupling of soil, temperature and stress fields during the freezing process of the soil, and the corresponding discrete equations and their solutions are given [7]. Miao Tiande [8] established the corresponding constitutive relations under the framework of the mixture theory of continuum mechanics. 4. The field equation for controlling the hydrothermal migration process of frozen soil is derived. Chen Feixiong [9] derived the principle of effective stress of frozen soil, the continuity equation of normal frozen soil unit and the energy conversion and transfer equation of each phase composition, and proposed the theoretical framework of the governing differential equation of normal frozen soil. Chen Feixiong [10] proposed a theoretical framework of coupled porous multiphase media of water, heat and force, and discussed a simple three-field coupling model of semi-connected semi-closed unsaturated pores. Li Ning [11] systematically deduced the differential governing equations of the three-field coupling problem of temperature, deformation and water fields in soil, ice and water in frozen soil, and developed the corresponding three-field coupling numerical analysis of frozen soil. CDST, and the ground temperature change and subgrade pavement deformation measured by the Huashixia test subgrade of National Highway 214 were compared and verified.

Throughout the domestic and foreign scholars on the mechanism of freezing and thawing, most of the research is mainly focused on subgrade, freezing method construction, slope stability analysis, etc. [12-17], and the research of deformation mechanism of foundation pit in seasonal frozen soil area has not been deepened. In this paper, numerical simulation method is used to establish the numerical model of thermal coupling of foundation pit under freezing and thawing, and the internal force and deformation law of foundation pit support under freezing and thawing are revealed. Provide theoretical basis and reference for the control and construction of foundation pit deformation in seasonal frozen soil areas.

II. THERMAL COUPLING MODEL CONSIDERING FREEZE-THAW ACTION

Temperature field Eq.1 introducing the concept of equivalent water content.

$$\overline{C}\,\partial T/\partial t = div(\lambda grad T) + L\rho_w\,\partial\theta_w/\partial t \tag{1}$$

The temperature boundary conditions are: $T|_s = T_b$, or $\left.\dfrac{\partial T}{\partial n}\right|_s = T_b$、 or $\left.\left(\dfrac{\partial T}{\partial n} + T\right)\right|_s = T_b$

The initial conditions of the temperature field are: $T|_{t=0} = T_0$

Introducing the equivalent water content of the seepage field Eq.2.

$$\frac{\partial\theta_w}{\partial t} = \frac{\partial}{\partial x}(D(\theta_u)\frac{\partial\theta_u}{\partial x}) + \frac{\partial}{\partial y}(D(\theta_u)\frac{\partial\theta_u}{\partial y}) + \frac{\partial k(\theta_u)}{\partial z} + \frac{\partial\varepsilon}{\partial t} \tag{2}$$

Eq.3 is for the relationship between stress and strain of soil elements.

$$\{\sigma\} = [D](\{\varepsilon\} - \{\varepsilon_0\}) \tag{3}$$

In the Eq. 3, $[D]$ is for the elastic matrix, $\{\sigma\} = \{\sigma_x, \sigma_y, \tau_{xy}\}$, $\{\varepsilon\} = \{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}$, $\{\varepsilon_0\} = \dfrac{1}{3}\{\varepsilon_v, \varepsilon_v, 0\}$

Introducing the damage factor $D = \dfrac{X_1 - X_2}{X_1}$ into the elastic matrix, Eq.1, Eq.2, and Eq.3 constitute the basic equation of water-thermal-force coupling considering freeze-thaw damage[18]. The determination of the physical parameters and the initial boundary temperature conditions need to be specifically combined with the model experiment, determined by fitting.

III. 3D NUMERICAL MODEL

A. Project Overview

The second phase pit project of Shenyang Dongsen CBD Commercial Plaza is located in the north of Shifu Road, Heping District, Shenyang City, east of Beisanhao Street. The main body is a 28-storey building and a 55-storey complex. The podium is 2-5 floors. Framework. The second basement is integrated into one, the bottom of the project is about -12 m deep, and the deepest part of the project is 14 m underground. . The importance level of the project is Grade 1, the site complexity is Grade II, the foundation complexity is Grade II, the geotechnical engineering survey grade is Grade A, and the foundation design grade is Grade A.

After a certain simplification of the foundation pit boundary in FLAC3D, a three-dimensional model of foundation pit and pile anchor support structure is established, as shown in Fig. 1, Fig. 2 and Fig. 3. The boundary conditions are model boundary x=0 m, x=166 m, y=0 m, y=116 m, z=0 m. The distance between the side boundary of the calculation area and the edge of the foundation pit is greater than 3 times the depth of the pit, and the freedom of the bottom surface is fixed . The soil layer parameters are obtained by the routine test and freeze-thaw property test in the references[18]. The material parameters and construction load of the pile-anchor support structure are set according to the actual conditions. For the foundation pit and supporting structure model after the foundation pit excavation is completed, the model is adopted. Set the ambient temperature parameter to simulate the cooling process during the winter. The temperature gradient from 30 ° C to 20 ° C, from 20 ° C to 10 ° C, from 10 ° C to 0 ° C, from 0 ° C to -10 ° C, from -10 ° C to -20 ° C, respectively The numerical calculation of the five cooling processes is carried out, and the internal force and deformation cloud diagram of the foundation pit are obtained.
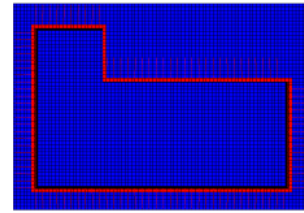

FIGURE I. TOP VIEW OF FOUNDATION PIT MODEL

TABLE I. SOIL PARAMETER VALUES

| Soil name	Soil parameter				
	Thickness /m	Soil severity /(kN/m³	Cohesion /kN	Internal friction angle /(°)	Modulus of deformation /MPa
Miscellaneous	2.1～5.4	17	10	10	12
Silty clay	0.5～1.1	18.2	29.9	12	10
Silt	0.2～1.5	18.1	27.1	13.1	11
coarse sand	1.5～7	17.5	2.8	27.4	20
Gravel sand	2.9～8.5	18	4.1	27.4	33.2
Clay soil	0.5～4.2	18.3	27.2	9.5	16
Boulder	4.5～11.4	18	0	36.9	35.9
Coarse sand	0.7～5.2	18	4.5	27.3	23.4
Gravel sand	3.7～9.9	18	0	37.3	34.2
Silty clay	0.8	17.5	34.8	9.0	10
Boulder	2.2～4.1	18	0	37.1	39.4
Gravel sand	3.0～5.6	18	0	37	34.2
Boulder	1.8～4.7	18	0	38	40
Mudstone	7.6～45.5	20.0			30
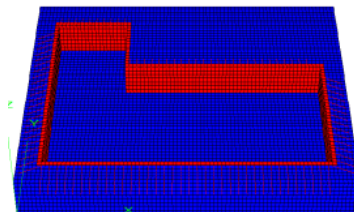
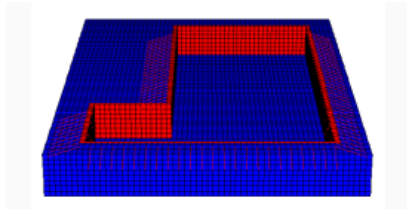FIGURE II. FRONT VIEW OF FOUNDATION PIT MODEL

FIGURE III. SIDE VIEW OF FOUNDATION PIT MODEL

B. Numerical Calculation of Cooling Process and Internal Force and Deformation Analysis of Foundation Pit
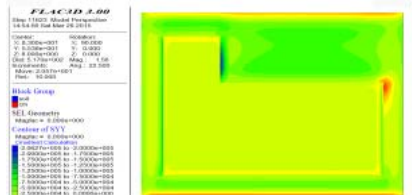
The deformation and stress diagram of the soil around the model after the completion of the excavation to the temperature of 30 °C is shown in Fig. 4. The subgraphs are displacement diagram, Z-direction stress diagram, X-direction stress diagram, and Y-direction stress diagram. In order to further observe the deformation, the deformation amount of the front state is cleared, and the deformation amount of the next state is calculated. Therefore, the displacement maps of different temperatures studied later are obtained when the displacement of the previous temperature is zeroed. Therefore, the displacement represented by the displacement map is generated during the corresponding temperature change.
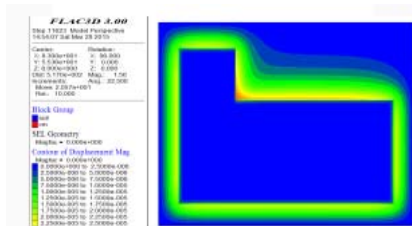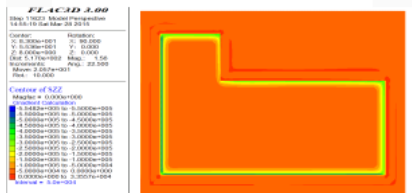

(A) HORIZONTAL DISPLACEMENT OF FOUNDATION PIT
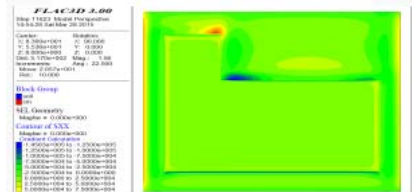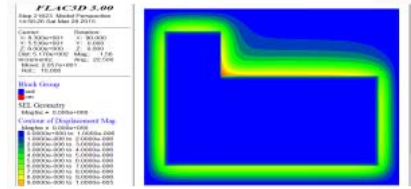

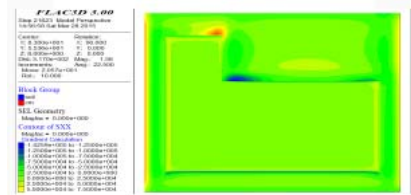(B) X DIRECTION STRESS

(C) Y DIRECTION STRESS

(D) Z DIRECTION STRESS

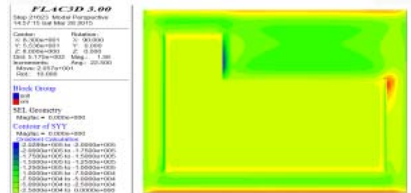FIGURE IV. DEFORMATION AND STRESS OF FOUNDATION PIT AT 30 ℃

When the temperature is lowered from 30 °C to 20 °C, the deformation of the foundation pit is simulated. Then, according to the thermal coupling model of FLAC3D, the solution is solved. I got the corresponding vector figure 5.
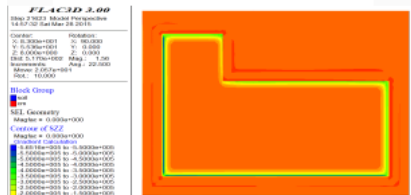

(A) HORIZONTAL DISPLACEMENT OF FOUNDATION PIT

(B) X DIRECTION STRESS

(C) Y DIRECTION STRESS

(D) Z DIRECTION STRESS

FIGURE V. FOUNDATION PIT DEFORMATION AND STRESS FROM 30 ℃ TO 20 ℃

When the temperature is reduced from 20 °C to 10 °C, the deformation of the foundation pit is simulated. Then, according to the thermal coupling model of FLAC3D, the solution is solved. I got the corresponding vector figure 6.

(A) HORIZONTAL DISPLACEMENT OF FOUNDATION PIT
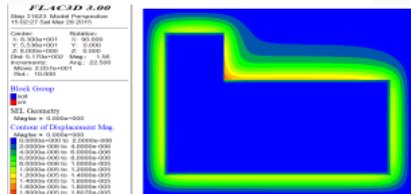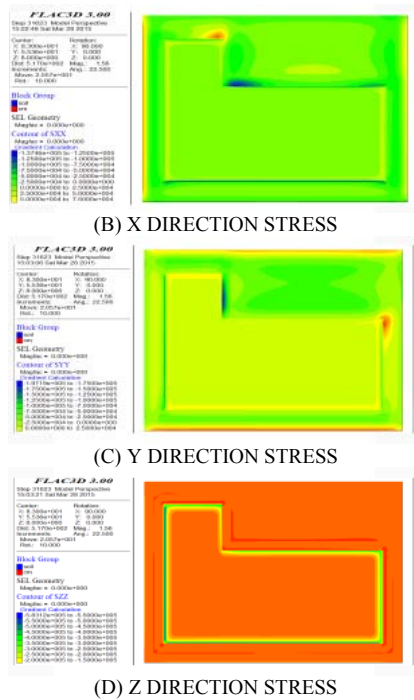
(B) X DIRECTION STRESS

(C) Y DIRECTION STRESS

(D) Z DIRECTION STRESS

FIGURE VI. FOUNDATION PIT DEFORMATION AND STRESS FROM 20 ℃ TO 10 ℃

When the temperature drops from 10 °C to 0 °C, the deformation of the foundation pit is simulated. After solving according to the thermal coupling model of FLAC3D, the corresponding vector figure 7 is obtained.
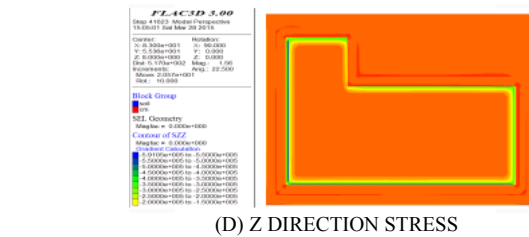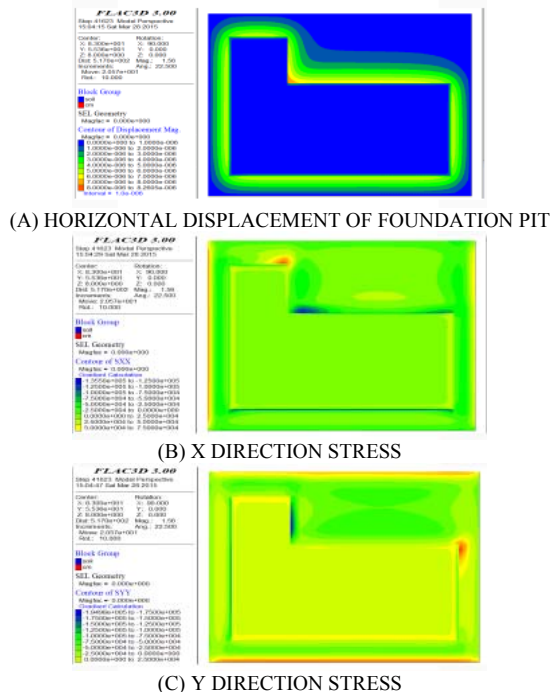

(A) HORIZONTAL DISPLACEMENT OF FOUNDATION PIT

(B) X DIRECTION STRESS

(C) Y DIRECTION STRESS

(D) Z DIRECTION STRESS

FIGURE VII. FOUNDATION PIT DEFORMATION AND STRESS FROM 10 ℃ TO 0 ℃

When the temperature drops from 0 °C to -10 °C, the deformation of the foundation pit is simulated. Then, according to the thermal coupling model of FLAC3D, the solution is solved. I got the corresponding vector figure 8.

(A) HORIZONTAL DISPLACEMENT OF FOUNDATION PIT

(B) X DIRECTION STRESS

(C) Y DIRECTION STRESS

(D) Z DIRECTION STRESS

FIGURE VIII. FOUNDATION PIT DEFORMATION AND STRESS FROM 0 ℃ TO -10 ℃

When the temperature drops from -10 °C to -20 °C, the deformation of the foundation pit is simulated. Then, according to the thermal coupling model of FLAC3D, the solution is solved. I got the corresponding vector figure 9.
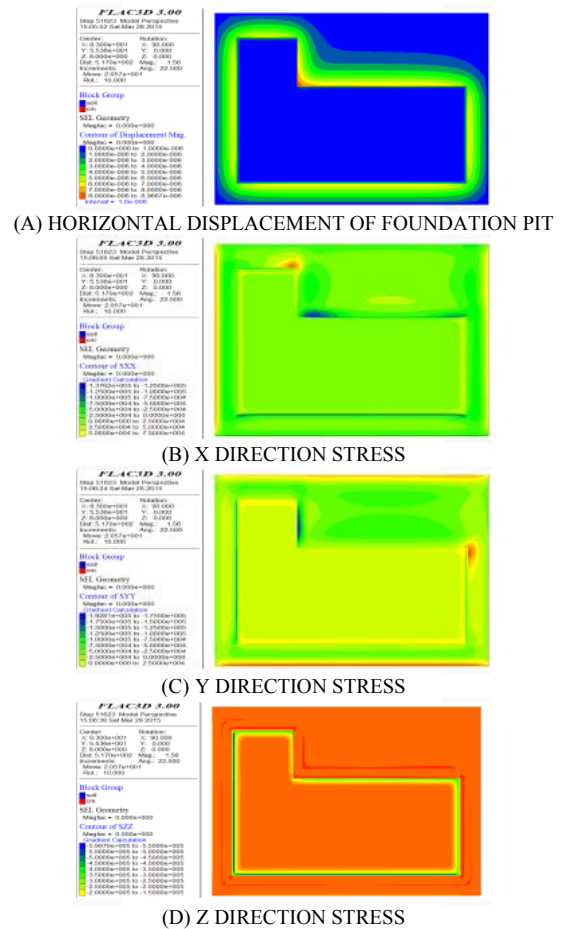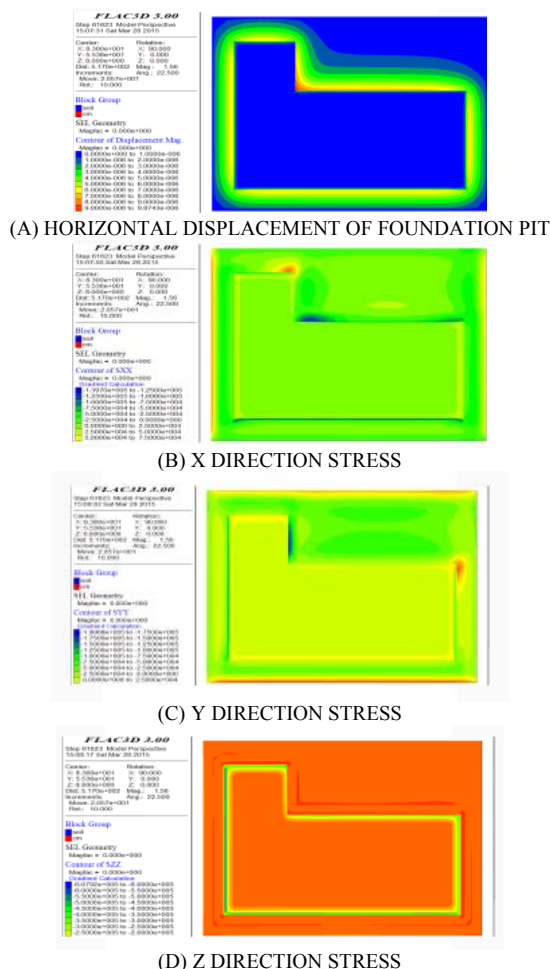
(A) HORIZONTAL DISPLACEMENT OF FOUNDATION PIT

(B) X DIRECTION STRESS

(C) Y DIRECTION STRESS

(D) Z DIRECTION STRESS

FIGURE IX. FOUNDATION PIT DEFORMATION AND STRESS FROM -10 ℃ TO -20 ℃

It can be seen from Fig. 4, Fig. 5, Fig. 6, Fig.7, Fig.8 and Fig.9 that the displacement of the foundation pit is regularly distributed along the periphery of the foundation pit, and the displacement distribution in the middle area on each side is large, from the middle to the two. The displacement of the end is gradually reduced, and the displacement is the largest in the positive angle area of the foundation pit.

During the temperature change, the displacement and stress concentration areas change little. For the total displacement map, the change is concentrated around the periphery of the foundation pit, and the closer to the base pit, the larger the displacement. In particular, the upper part of the figure goes deep into the corner of the foundation pit, and the displacement is most obvious. The X-direction stress has a tensile and compressive distribution at the periphery of the foundation pit. The area with large tensile stress is distributed in the upper part of the figure to the corner of the foundation pit. The upper part of the compressive stress map penetrates the corner above the corner of the foundation pit. The Y-direction stress has a tensile and compressive distribution at the periphery of the foundation pit. The area with large tensile stress is distributed in the upper part of the figure to the position near the pit between the corner of the foundation pit and the upper corner. Compared with the

tensile stress, the compressive stress is rarely distributed at the corner of the upper pit of the upper right side of the figure. The Z direction stress is compressive stress around the foundation pit.

For the above-mentioned stress and deformation at different temperatures, see Table 2.

It can be seen from Table 2 that there is a significant decrease in the maximum displacement from 30 °C to 0 °C, but the displacement is slightly increased from 0 °C to -20 °C. However, the displacement during the entire temperature change process is not always large. The maximum stress changes in the X and -X directions are small within 5×10^4 Pa, so there is no change in the FLAC3D cloud image during the whole temperature change process. The maximum stress change in the -Y direction is small within 2.5×10^5 Pa, so there is no change in the FLAC3D cloud image during the whole temperature change process. The maximum stress in the Y direction has increased, but it is always less than 2.5×10^5 Pa. The maximum stress changes in the Z and −Z directions are all within 5×10^4 Pa, so there is no change in the FLAC3D cloud image during the whole temperature change process. Based on the above analysis, it can be concluded that the effect of cooling on the displacement of foundation pit and supporting structure is relatively obvious, but has little effect on the stress of foundation pit support.

IV. CONCLUSION

The following main conclusions are obtained by establishing the thermal coupling model and numerical simulation of the foundation pit considering the freezing and thawing effect:

(1) Introducing the freeze-thaw damage factor into the basic equation of thermo-mechanical coupling, and establishing a thermo-mechanical coupling model considering freeze-thaw damage.

(2) Through the numerical calculation results, it can be seen that the deformation of the foundation pit is most affected by the temperature at the positive angle during the cooling process close to 0 ° C. The displacement of the foundation pit is the largest during the cooling process from 0 ° C to -10 ° C.

(3) The displacement of the foundation pit is not large during the whole temperature change. There is a significant decrease in the maximum displacement from 30 ° C to 0 ° C, but the displacement is slightly increased from 0 ° C to -20 ° C. It can be seen from the stress cloud diagram that the effect of temperature change on internal forces is relatively small.

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