# Theoretical and Test Study on Dynamic Characteristics of Thin-Layered Sandy Frozen Soil in Blasting

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***Abstract*—In order to understand the stress changes of various points in sandy frozen soil, tension-compression conversion, fissure development on the surface, the rupture process, the expansion speed and scope of frozen soil duing blasting, the dynamic characteristics of thin-layered sandy frozen soil were analyzed in this paper. The blasting process of frozen soil is regarded as a dynamic pressure operation process of gas expansion chamber under thin plate. The gas pressure in blasting chamber obtained by adiabatic gas state equation is approximate close to the actual expansion pressure. At the same time, a moment of frozen soil blasting process is regarded as a model that a peripherally-fixed solid circular plate is suffered to a concentrated force in the center of circle. Through calculation and blasting funnel tests we can see that the frozen soil is suffered to much smaller force along horizontal direction than normal direction. Along with the time and expansion of blasting chamber, pressure of frozen soil is quickly reduced. And it is discovered that regardless of any stage of explosive, there appears the critical point of changes from tension to compression along the direction from explosive center to the all-around within a radius of about 0.9 m. This model can provide a theoretical guidance for the analysis of dynamic stress and the selection of blasting parameters for frozen soil blasting.**

***Index Terms*—frozen soil blasting, sandy frozen soil, explosive pressure, deflection, numerical simulation, blasting funnel test**

## I. INTRODUCTION

The blasting characteristics of frozen soil is related to the physical and mechanical indicators of frozen soil (including tensile strength, compressive strength, elastic modulus, compressive modulus, coefficient of compressibility, wave velocity, frozen soil temperature, frozen soil ingredients and ice content etc.). And it is also related to blast impulse, operation time and operation form. Qinyong Ma has done the blasting funnel model test [1] of frozen clay and sand in the temperature of -7, -12, -17 ℃ according to the similarity theory and Livingston blasting funnel theory. He has also done the model investigation of blasting funnel and blasting characteristics of frozen soil (1997). In addition, he has done blasting experiment and method study of permafrost and artificial frozen soil [2]（2004）. Hongxian Fu, Shuyu Feng and Zhiyi Zhang have taken the blasting parameters studies [3] of frozen soil excavation in Qinghai-Tibet Railway through the field funnel blasting test of spherical cartridge and column cartridge (2004). Nianhua Yang has introduced and compared the principle of determination and selection [4] of frozen soil blasting parameters in different frozen depths through the example of a frozen soil blasting (2005). Junbing Zhang, Weidong Pan and Hongxian Fu have done some studies [5] in the blasting funnel test and the blasting test method of a high-ice-content frozen soil at Tuotuohe Region of Qinghai-Tibet Plateau. Yongmou Zhang and Feihong Xie introduced their studies about the blasting characteristics of thin-layered sandy frozen soil [6].

By studying the relationships among the frozen soil characteristics, explosive load and blasting depth, the best depth and the largest volume of unit cartridge are obtained in this paper. And then the best blasting parameters are deduced. This research studies the blasting rupture behavior and dynamic damage process of thin layered-sandy frozen soil, adopting elastodynamics method. The physical-mechanics indicators of frozen soil are intrinsic factors, and blasting impulse, operation time and operation form are extrinsic factors. It is of great practical significance and theoretical significance in researching the destructive behavior and the characteristics of frozen soil under blasting.

## II. MODEL and TIME-DEPENDENT PRESSURE

There are great differences in the mechanical response of frozen soil under explosive shock loads and quasi static loads. These kinds of differences are related to the

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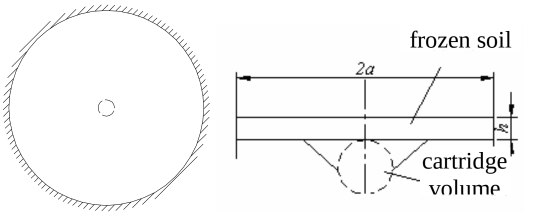
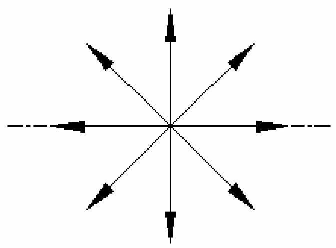
features of shock loads. Firstly comes instantaneity. The operation time of shock load is normally termed in milliseconds, microseconds or even nanoseconds. Secondly comes high-intensity. When explosion takes place in frozen soil, the pressure applied on the surface of frozen soil reaches 2 ～ 5Gpa. When cartridge is embedded in frozen soil and after detonation at the center of cartridge, the detonation wave is propagated to all directions with the same speed which depends on the type of explosive. Before the stress wave arrives at the point a little far away from the surface of cartridge, detonation wave has spread to the entire cartridge, and excessive pressure of explosive gas begins to apply on all points contacting with frozen soil at the same time. Therefore, the entire blasting process of frozen soil can be seen as the follows: initiation stage → the formative stage of compressive cavity → the extension process of radial fissure → the expansive stage of compressive cavity → the thin plate being cut into blocks, gas leaking. This is shown in Fig. 1. After the dynamic process of cartridge blasting, there remains a cavity full of detonation gas with certain pressure and temperature in frozen soil. There form four critical areas in turn around the cavity. The fluid zone is closest to the explosion chamber, which is then frozen since of the temperature difference. The followed areas are rupture zone, plastic deformation zone and elastic zone which is the farthest away from the explosion chamber.

In blasting calculation, the expansive pressure theory of blasting gas was used. The destruction of brittle medium caused by explosion is mainly due to the result of the expansive pressure of blasting gas doing work. The dynamic action of stress wave and the effects of explosion heat on medium were ignored. The force produced by blasting evenly distributed in the soil interface formed by the cavity. Soil cohesion was considered as the vertical uniformly distributed force because of the instantaneity of fracture. The force distribution range can be determined by the actual amount of explosives. The adhesive force amplification factor K was taken into account for soil cohesion because of the instantaneity of fracture. The amplification factor K was taken as 1.0, 1.5, and 2.0 in this paper. The expanding gas leaks out of the cavity in the moment of soil cracking. Because of its instantaneity, it was not taken into account for the blasting force in the calculation. The fracture between permafrost and non-frozen soil is carried out in the moment of explosion. The effects of other unknown factors and secondary factors were not considered temporarily.

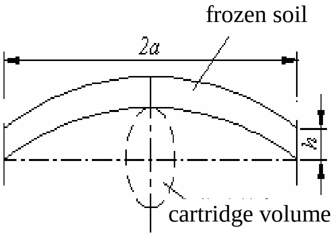


*a* initiation stage
cavity

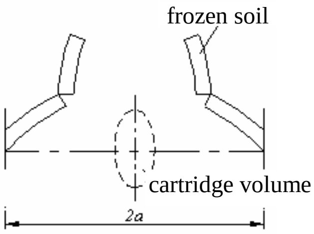
*b* the formative stage of compressive



*c* the extension process of radial fissure



*d* the expansive stage of compressive cavity



*e* thin plate being cut into blocks, gas leaking

Figure 1. Frozen soil expansive process

Through calculating the volume change of cartridge before and after explosion, the expansion moving speed of thin plate can be obtained with the change of time in blasting process. And the changes of vertical value b and transversal value a can also be calculated by the following equation.

$$\Delta b = v_t t . \tag{1}$$

Where $v_t$ —the expansions speed in the moment of t;

$\Delta b$ —variation of vertical value.

$\Delta b$ at the situation of two different soil has been calculated.

$$b_{t2} = b_{t1} + \Delta b . \tag{2}$$

Where $v_t$ —vertical value in the moment of $t_1$;

$b_{t2}$ —vertical value in the moment of $t_2$ .

Average velocity was used in calculation. Blasting duration was taken as 200ms. Assume that the proportionality of vertical value/radius of compressive cavity always remain the same in blasting process. Then the radius variation of compressive cavity in the moment of t can be obtained through Table 1 [7,8,9]. Table 2 shows the calculation results.

After analyzing the data of experimental explosive load, vertical value and cavity radius, we can get the rule of explosive load with vertical value/cavity radius. This is shown in Fig. 2. And the volume of cavity in the moment of t can be calculated by cubature formula of ellipsoids.

TABLE I.
THE COMPRESSIVE CAVITY PARAMETERS OF COARSE SANDY-SOIL ( $\rho$ =1500 KG/GM$^3$, $\Omega$=15~20%) IN DIFFERENT EXPLOSIVE LOADS

| Explosive load /g | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 |
|---|---|---|---|---|---|---|---|---|
| Radius of cavity $a$/cm | 4.0 | 5.25 | 10.0 | 13.0 | 13.8 | 15.0 | 18.0 | 19.0 |
| Vertical value $b$/cm | 6.7 | 7.26 | 11.52 | 14.51 | 15.09 | 16.20 | 15.95 | 16.84 |
| Cavity volume $V$ /cm$^3$ | 499 | 838 | 4823 | 10267 | 12031 | 15260 | 21636 | 21636 |
| Vertical value/cavity radius | 1.69 | 1.38 | 1.15 | 1.12 | 1.09 | 1.08 | 0.89 | 0.88 |
| Movement duration /ms | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Average velocity /m/s | 3.35 | 3.63 | 5.76 | 7.26 | 7.55 | 7.98 | 8.10 | 8.42 |

TABLE II.
RADIUS OF COMPRESSIVE CAVITY IN THE MOMENT OF T UNDER DIFFERENT EXPLOSIVE LOAD

Unit: cm

| Explosive load /g<br>Moment t /ms | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 |
|---|---|---|---|---|---|---|---|---|
| 20 | 0.067 | 0.073 | 0.115 | 0.145 | 0.149 | 0.160 | 0.162 | 0.168 |
| 40 | 0.134 | 0.145 | 0.230 | 0.290 | 0.298 | 0.319 | 0.324 | 0.337 |
| 60 | 0.201 | 0.218 | 0.346 | 0.435 | 0.447 | 0.479 | 0.486 | 0.505 |
| 80 | 0.268 | 0.290 | 0.461 | 0.580 | 0.596 | 0.638 | 0.648 | 0.674 |
| 100 | 0.335 | 0.363 | 0.576 | 0.726 | 0.745 | 0.798 | 0.810 | 0.842 |
| 120 | 0.402 | 0.436 | 0.691 | 0.871 | 0.895 | 0.957 | 0.972 | 1.010 |
| 140 | 0.469 | 0.508 | 0.806 | 1.016 | 1.044 | 1.117 | 1.134 | 1.179 |
| 160 | 0.536 | 0.581 | 0.922 | 1.161 | 1.193 | 1.276 | 1.296 | 1.347 |
| 180 | 0.603 | 0.653 | 1.037 | 1.306 | 1.342 | 1.436 | 1.458 | 1.516 |
| 200 | 0.670 | 0.726 | 1.152 | 1.451 | 1.491 | 1.595 | 1.620 | 1.684 |

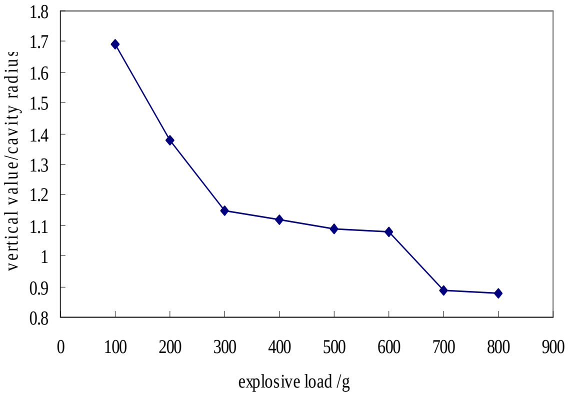


Figure 2. Explosive load with vertical value/cavity radius

the volume of detonation cavity,

$$V = \frac{4}{3}\pi a^2 b \cdot \quad (3)$$

Herein the volume in moment t is obtained according to the following equation,

$$\frac{P_{s1}V_1}{T_1} = \frac{P_{s2}V_2}{T_2} \cdot$$

The variation of pressure intensity can be calculated. According to the formula of adiabatic process, the above equation can be simplified as the follows:

$$P_{s2} = \frac{P_{s1}V_1}{V_2} \cdot \quad (4)$$

The initial pressure intensity at the moment of blasting is:

$$P_{S0} = \frac{1}{4}\rho_0 v_d^2 \cdot \quad (5)$$

Where $\rho_0$ —density of explosive, 0.7 g/cm$^3$;

$v_d$ —speed of explosive, 3200 m/s.

Thus, the change of pressure intensity in compressive cavity can be calculated.

The change of pressure in the horizontal plane can also be calculated by the following formula.

$$P = P_S S \cdot \quad (6)$$

Where P—pressure;

S—projected area of ellipsoids in the horizontal plane.

There exists a certain relationship between the pressure P and time t. The following is their relationship [10]:

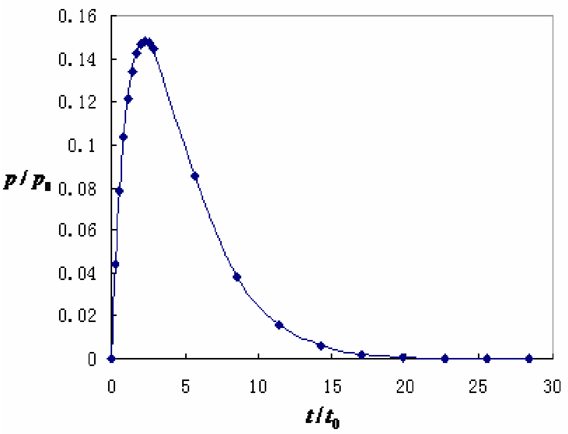
$$P = P_0\left(e^{-\alpha t} - e^{-\beta t}\right).$$

Where P is the pressure that soil is suffered to at the moment of blasting. t is blasting time. $P_0$ is the peak of pressure.

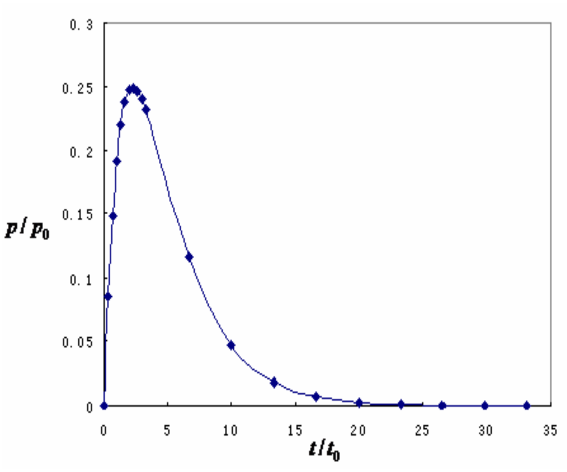
The above formula can be rewritten as follows [11,12]:

$$P = P_0\xi\left(e^{-\alpha t} - e^{-\beta t}\right). \tag{7}$$

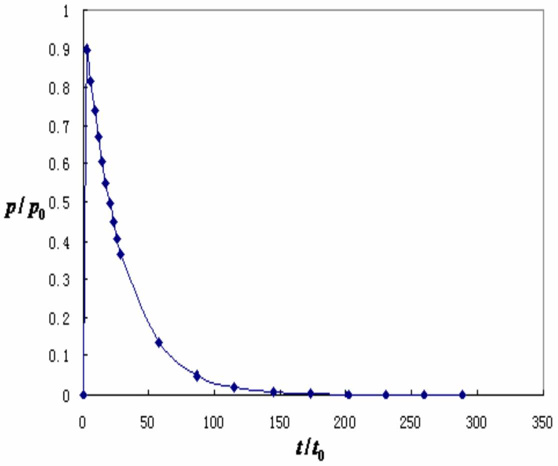
When $\xi = 1/\left(e^{-\alpha t} - e^{-\beta t}\right)$, $t_0 = [1/(\beta-\alpha)]\log(\beta/\alpha)$, the relationship curve between pressure and time can be obtained in the moment of $t_0$ =10, 100, 500, 1000μs. We can substitute different values of α and β into (7) to calculate the relationship curves between pressure and time as shown in Fig. 3.



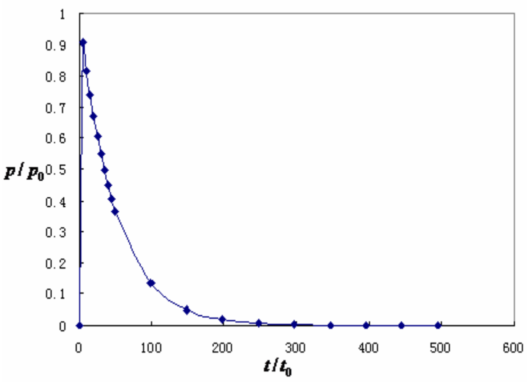
*a β/α*=1.5



b *β/α*=2



*c β/α*=50



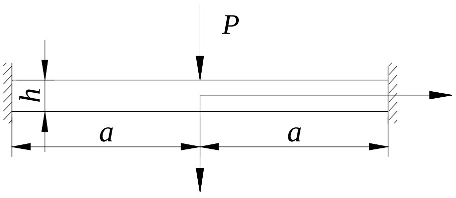
*d β/α*=100

Figure 3. Time-dependent pressure curve at different *β/α*

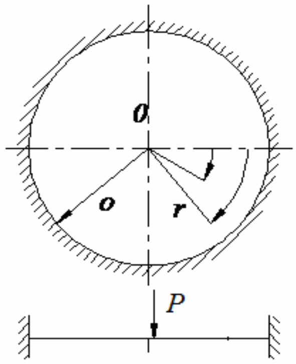
From Fig. 3 we can see that pressure changes with time at different β/α. When β/α is small, the peak pressure is relatively small. When β/α is big, the peak pressure is relatively large, and the peak pressure rises quickly. The condition of small β/α is suitable for high compressibility and the developed joint fissure of chamber rock. According to the geotechnical properties of pre-made test, β/α is taken as 50 in this paper.

## III. ELASTODYNAMICS NUMERICAL SOLUTION of BLASTING FROZEN SOIL

A moment of the blasting process of frozen soil is regarded as a peripherally-fixed solid circular plate that is suffered to a concentrated force P applied at the center of circle with a radius of a. This is shown in Fig. 4. The elastic circular plate that is suffered to an unit transversal concentrated load at the polar coordinate ($\xi,\varphi$) is taken as the basic system as shown in Fig. 4b. The fundamental solution to the deflection equation of the elastic plate is [13,14,15].



*a* calculation model



*b* circular plate model in polar coordinate

Figure 4. Mechanical computation model

$$\omega_1(r,\theta,\xi,\varphi)= R_0' + \sum_{m=1}^{\infty} R_m' \cos m(\theta-\varphi)(0 \le r \le \xi) \cdot \qquad (8)$$

$$\omega_1(r,\theta,\xi,\varphi)= R_0 + \sum_{m=1}^{\infty} R_m \cos m(\theta-\varphi)(\xi \le r \le a) \cdot \qquad (9)$$

Where

$$R_0' = \frac{1}{8\pi D}[(r^2+\xi^2)\ln\frac{\xi}{a}+\frac{1}{2a^2}(a^2+r^2)(a^2-\xi^2)],$$

$$R_0 = \frac{1}{8\pi D}[(r^2+\xi^2)\ln\frac{r}{a}+\frac{1}{2a^2}(a^2-r^2)(a^2+\xi^2)],$$

$$R_1' = -\frac{\xi^3}{16\pi D}[(\frac{2(a^2-\xi^2)r}{a^2\xi^2}+\frac{(a^2-\xi^2)^2r^3}{a^4\xi^4}-\frac{4r}{\xi^2}\ln\frac{a}{\xi},$$

$$R_1 = -\frac{\xi^3}{16\pi D}[\frac{1}{r}+(\frac{2(a^2-\xi^2)r}{a^2\xi^2}-\frac{(2a^2-\xi^2)^2r^3}{a^4\xi^2}-\frac{4r}{\xi^2}\ln\frac{a}{r},$$

$$R_m' = \frac{\xi^m}{8m(m-1)\pi D}\{\frac{r^m}{a^{2m}}[(m-1)\xi^2-ma^2+\frac{a^{2m}}{\xi^{2m-2}}] +(m-1)\frac{r^{m+2}}{a^{2m}}[1-\frac{m}{m+1}\frac{\xi^2}{a^2}-\frac{1}{m+1}(\frac{a}{\xi})^{2m}]\},$$

$$R_m = \frac{\xi^m}{8m(m-1)\pi D}\{\frac{r^m}{a^{2m}}[(m-1)\xi^2-ma^2+(m-1)r^2 -\frac{m(m-1)}{m+1}\frac{\xi^2r^2}{a^2}]+\frac{1}{r^m}(r^2-\frac{m-1}{m+1}\xi^2)\},$$

The bending rigidity of circular plate is:

$$D=\frac{Eh^3}{12(1-\mu^2)} \cdot$$

The basic solution of internal force equation is [14]:

$$\sigma_x = -\frac{Ez}{1-\mu^2}\left(\frac{\partial^2\omega}{\partial x^2}+\mu\frac{\partial^2\omega}{\partial y^2}\right),$$

$$\sigma_y = -\frac{Ez}{1-\mu^2}\left(\frac{\partial^2\omega}{\partial y^2}+\mu\frac{\partial^2\omega}{\partial x^2}\right),$$

$$\tau_{xy} = -\frac{Ez}{1+\mu}\frac{\partial^2\omega}{\partial x\partial y} \cdot \qquad (10)$$

According to the above (10), normal stress and shear stress of x-axis and y-axis can be calculated separately. Where deflection $\omega$ is the deflection formula of mechanical computational model.

$$\omega = \frac{Px^2}{8\pi D}\ln\frac{x}{a}+\frac{P}{16\pi D}\left(a^2-x^2\right) \cdot \qquad (11)$$

Substituting (11) into the following (12) to calculate $\sigma_z$ of plate:

$$\begin{aligned}\sigma_z &= -\frac{E}{2(1-\mu^2)}\left[\frac{t^2}{4}\left(z-\frac{t}{2}\right)-\frac{1}{3}\left(z^3-\frac{t^3}{8}\right)\right]\nabla^4\omega \\ &= -\frac{Et^3}{6(1-\mu^2)}\left(\frac{1}{2}-\frac{z}{t}\right)^2\left(1+\frac{z}{t}\right)\nabla^4\omega\end{aligned} \quad . \qquad (12)$$

Where t is the thickness of plate. z is the z-axis coordinate of calculation position. E is modulus of elasticity in comperssion. $\mu$ is poisson's ratio. $\nabla^4\omega$ is Laplacian operator.

## IV. CASE STUDY

The thickness h of sandy frozen soil (ρ=1500 , ω=15~20%) is 0.26m. The center along the thickness of plate is taken as the origin of coordinate. The upper and lower boundaries of plate are $z=h/2$ and $z=-h/2$ separately. The elastic modulus is $E=0.5\times10^3\text{MPa}$. The Poisson's ratio is $\mu=0.2$. The explosive load of cartridge is 100g. Assume that the initial size of cartridge is $a=40\text{mm}$ and $b=67.7\text{mm}$. The calculation radius is taken as 10m.

Table 3 shows the calculation results.

Using the same approach, deflection under explosive load 200g was calculated as shown in table 4.

TABLE III.
PARAMETERS AT DIFFERENT MOMENT T UNDER EXPLOSIVE LOAD 100G

| moment t /ms | volume /$10^{-3}$m$^3$ | pressure in cavity /MPa | deflection variation /m | deflection /m |
|---|---|---|---|---|
| 20 | 3.62 | 442.10 | 0.689 | 0.689 |
| 40 | 11.96 | 133.80 | 0.310 | 0.999 |
| 60 | 28.45 | 55.97 | 0.174 | 1.173 |
| 80 | 55.48 | 28.70 | 0.111 | 1.284 |
| 100 | 95.50 | 16.67 | 0.077 | 1.361 |
| 120 | 152.00 | 9.72 | 0.053 | 1.414 |
| 140 | 226.00 | 7.08 | 0.044 | 1.458 |
| 160 | 322.60 | 4.81 | 0.034 | 1.492 |
| 180 | 443.00 | 3.61 | 0.028 | 1.520 |
| 200 | 588.00 | 2.72 | 0.023 | 1.543 |

TABLE IV.
PARAMETERS AT DIFFERENT MOMENT T UNDER EXPLOSIVE LOAD 200G

| moment t /ms | volume /$10^{-3}$m$^3$ | pressure in cavity /MPa | deflection variation /m | deflection /m |
|---|---|---|---|---|
| 20 | 11.18 | 789.23 | 1.539 | 1.539 |
| 40 | 46.56 | 189.45 | 0.369 | 1.908 |
| 60 | 121.96 | 72.32 | 0.141 | 2.049 |
| 80 | 252.54 | 34.93 | 0.068 | 2.118 |
| 100 | 453.44 | 19.45 | 0.038 | 2.155 |
| 120 | 739.81 | 11.92 | 0.023 | 2.179 |
| 140 | 1126.80 | 7.83 | 0.015 | 2.194 |
| 160 | 1629.57 | 5.41 | 0.011 | 2.205 |
| 180 | 2263.25 | 3.90 | 0.008 | 2.212 |
| 200 | 3043.01 | 2.90 | 0.006 | 2.218 |

The variation of deflection (Fig. 5) and variation of stresses (Fig. 6) in blasting process were solved. The result shows that the vertical stress is 20~30 times greater than the transverse stress (Fig. 6). Thus the vertical stress of plate is the dominant factor. The results are shown in Fig. 7.

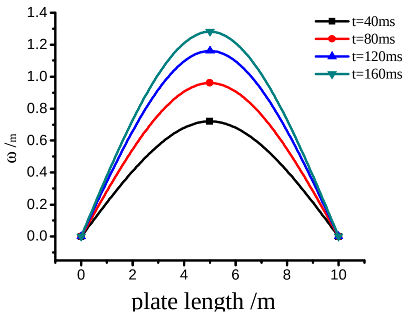
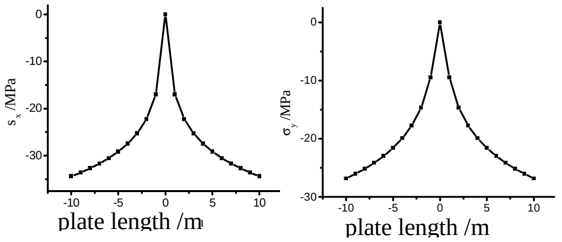
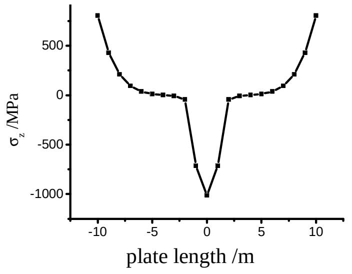


Figure 5. Deflection vs. time curve

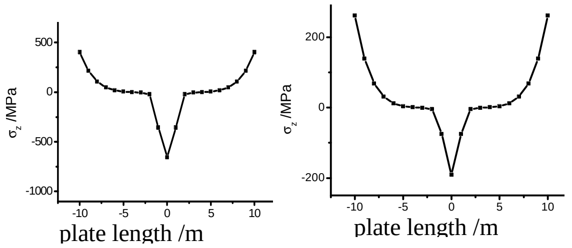


a $\sigma_x$ curve b $\sigma_y$ curve

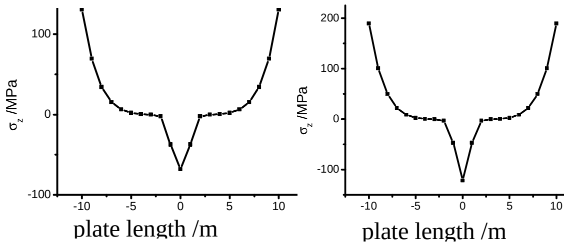


c $\sigma_z$ curve

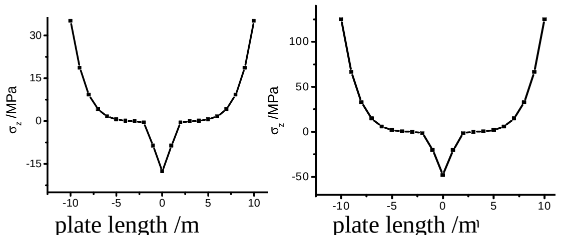
Figure 6. Stress curve at $t = 40\text{ms}, z = -h/2$



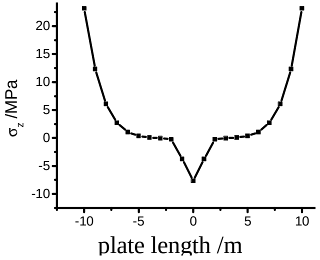
a $t = 40\text{ms}, z = 0$ b $t = 80\text{ms}, z = t/2$



c $t = 80\text{ms}, z = 0$ d $t = 120\text{ms}, z = 0$



e $t = 120\text{ms}, z = -t/2$ f $t = 160\text{ms}, z = 0$



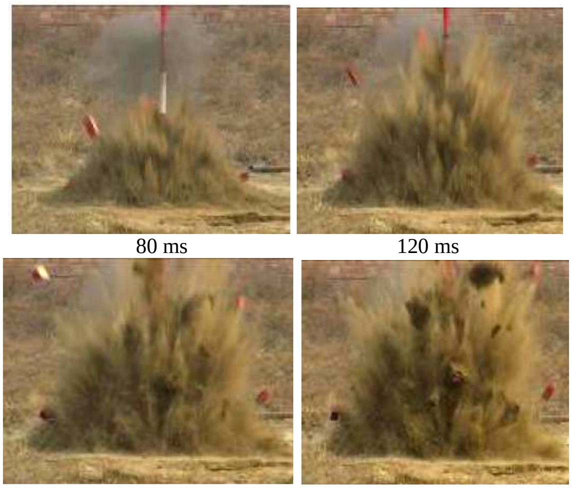
g $t = 160\text{ms} \quad z = t/2$

Figure 7. Stress curve of plate at different times

Through the above calculations, it can be understood the stress changes of the frozen soil on various points in blasting process. The stress of various points is changed with its own load conditions. At the same time, the state of stress changes in frozen soil and the appearance of tension-compression inflection point in thin layered-frozen soil under blasting pressure can be shown from the force diagram.

For the convenient of field observation, professional camera of CanonXM2 was used for the representative blasting tests to record the explosive movement process of plate of different mediums in the blasting funnel tests of thin plate. This is shown in Fig. 8. The camera frames shoot at 25 frames/sec. The distance from the shot object does not exceed 50m. And the height difference with explosive point is not greater than 1.0m. The explosive flash of the detonator above explosive point is taken as the initiation zero point. In order to improve the clarity of photographs and to analyze the photographs, the floating earth on the surface of plate has been removed before blasting for the observations of the fissure development on plate surface and the rupture process of thin plate, as well as for determining the moving speed and the expansion scope of plate. And markers have been set at and around the position of the least resistance line of the cartridge. At the same time, vertical benchmarks have also been set in the scope of shooting. The video image was processed and analyzed by computer to obtain the required photographs and data after shooting.

0 ms 40 ms



80 ms 120 ms

160 ms 200 ms

*a* thickness $h = 0.26$m

0ms 40ms

80ms 120ms

160ms

*b* thickness $h = 0.70$m

Figure 8. Blasting experiment of sandy frozen soil of different thickness

Frozen soil in Fig. 8a is relatively thin. Dust fog appears about the surface of frozen soil at the moment of initiation. Due to the sheltering of dust fog, it is difficult to see the development of cracks on soil surface. The initial expansion velocity was 3.3m/s. And the maximum expansion velocity was 9.0m/s. Frozen soil in Fig. 8b is relatively thick. The floating earth on the surface of plate in Fig. 8b was not removed before blasting. The reflected dust fog can be seen in the moment of initiation. The initial expansion velocity was 0.5m/s. And the maximum expansion velocity was 8.5m/s.

## V. CONCLUSION

(1) Through the numerical simulation of blasting features for thin-layered sandy frozen soil, it can be found that elastodynamics theory can be used to describe the mechanical characteristics of frozen soil in the process of blasting. The pressure at a moment of the expansive process of explosion cavity can be equivalently converted to a concentrated pressure that the thin plate is suffered to. And then the dynamic stress field and deflection of plate can be calculated step by step. This computational model is influenced greatly by the boundary conditions for the analysis of deflection. However it is more accurate for the calculation of dynamic stress field.

(2) Through calculating the volume change of blasting cartridge before and after explosion, the discipline of expansion moving speed of thin plate of frozen soil can be obtained along with the change of time in blasting process. The appropriate dynamic pressure at different times of blasting can be obtained, using different correction parameters of time-dependent pressure to correct the dynamic pressure.

(3) Through the stress calculation of layered frozen soil, we can see that the frozen soil is suffered to much smaller force along horizontal direction than normal direction. At the same time, the stress condition of frozen soil is also different at different times. The pressure applied on frozen soil is quickly reduced along with time and expansion of blasting cavity. And it is also discovered that at any stage of blasting, critical point changing from tension to compression appears along the center of explosive to all around within a radius of about 0.9m. This result is completely conformed to the result of blasting funnel tests.

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