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COMPACTION OF LOOSE SAND DEPOSITS USING BLASTING

COMPACTION DES DEPOTS DE SABLES MEUBLES A L'AIDE D'EXPLOSIFS

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Synopsis:
Blasting is the only economicaly feasible method for the compaction of the large areas of saturated loose sand deposits existing in the Lausitz region of Germany. A field experiment carried out to study the various phases during and after the blast and to be able to better understand the mechanisms underlying compaction blasting is presented. Results of measurements carried out to observe the development of pore water pressures, shock wave velocities, particle wave velocities and the compaction effect using static cone penetrometer tests are presented. Theoretical concepts which explain the various observations are presented and discussed.

INTRODUCTION

The Lausitz region in the eastern part of Germany is a major reservoir of lignite. The lignite deposits having thicknesses of about 10 m lie at a depth of about 50 m. The soil covering these deposits consists mainly of fine and medium sands. The lignite is mined using open pit mines, the main steps being:

- Ground water lowering upto the bottom of the lignite deposit
- Excavation upto the deposit and mining of the lignite
- Refilling of the mine
- Restoration of the natural ground water level

Owing to the fact that the complete mass of the original material that was removed cannot be refilled, a portion of the pit remains, resulting in the formation of slopes and a lake. The fill material has a rather uniform grain size distribution and a rounded grain form. As a result of the filling procedure, the above mentioned soil properties and the rising of the ground water table, an extremely loose saturated sand fill is formed. Such fills have a strong tendency towards spontaneous liquification. In the case of a liquification, several million cubic meters of soil can be set into motion and pose a danger to man and nearby structures. In the Lausitz region, very large areas made up of such fills exist (about 170 km^2) and more than 35 instances of spontaneous liquification have been reported [4]. A remediation of this problem is urgently required.

The most obvious and probably the only way of remediation is the compaction of these deposits. Several technologies are available for this. However, considering the large depths (upto 50 m) and the enormous volumes (order of one billion cubic meters), the only economically feasible method is that of compaction using blasting. This method has been used in several parts of the world, e.g.[1], [5]. However, a consistent theoretical and mechanical model to explain the various phenomena during blasting and the resulting compaction effect is not available. This paper describes a field experiment conducted in the eastern part of Germany, to study the various phases during and after the blast so as to be able to better understand the mechanisms underlying compaction blasting.

THEORETICAL CONCEPTS

The various stages during compaction blasting may be described as follows:

1. Formation of a nearly spherical space after the explosion owing to the very high pressures of the explosion gases. The formation of this space is accompanied by the propagation of a shock wave (a wave accompanied by large plastic deformations and a destruction of the grain structure) .
2. Formation of a suspension of sand and water around the spherical space. This suspension is termed as a "suspension bubble".
3. Propagation of elastic waves into the far field of the explosion.
4. Development of excess pore water pressures as a result of the gas pressures and the intense shear deformations.
5. Dissipation of the excess pore water pressures and compaction of the soil.

6. Rising up of the suspension bubble (depending on its location and size) to the ground surface and the formation of a crater.

In the following, theoretical models available for the various stages mentioned above are briefly presented and discussed.

Near Field

A theory for the dynamic expansion of a spherical space in saturated granular soil has been presented by Nowacki et. al. [9]. This thoery takes into account the compressibility of the two phase medium. However, in reality a relative movement of water and soil particles takes place resulting in a separation. This results in regions with lower and higher water contents and correspondingly to compacted and loosened regions.

Kolymbas [7] has developed a theory to describe this phenomenon based on the conditions of conservation of mass and momentum seperately for water and soil. For the interaction between soil and water, Darcy's law is used. It is shown that the explosion gases are surrounded by a compacted zone having a lower water content and this zone is surrounded by a zone of sand suspension. Based on this model the size and development of the two zones as a function of time can be numerically simulated.

Far Field

For the wave propagation in the far field, an assumption of spherical symmetry is not valid anymore owing to the presence of layers and of the ground surface. The following wave types are to be taken into consideration.

- P-waves, where the movement of the water and soil particles is identical. This wave type is without doubt present. However, as an elastic wave with no permanent effect on the soil, this wave type has no influence on the compaction effect of the soil.
- S-waves. When the soil shows a contractant behaviour, then this wave type should play a key role in the explanation for the development of excess pore water pressures following undrained shearing. It is clear that loose soils will have a tendency to compact when they are subjected to shearing. The excess pore water pressures developed in this process result in a lowering of the effective stresses and as a result in the lowering of stiffness and strength of the grain structure. In the limiting case, when the effective stresses are zero, the soil-water mixture appears to be a fluid. This phenomenon is fairly well understood and can also be numerically simulated using appropriate constitutive laws (e.g. the hypoplastic constitutive laws developed in Karlsruhe).
- Mixed waves (e.g. Rayleigh waves). These waves arising due to the existence of boundaries such as the ground surface can also play an important role in the compaction because they are coupled with shearing and contractancy of the soil.

Pore Pressure Development

In the near field, the detonation evidently produces a tremondous pore pressure increase for a rather short time. Inside the shock wave, which dies out at a certain distance, a bubble of suspension is left with a certain excess water pressure. The internal bubble of detonation gases acts as a pressure supply for the bubble. As a consequence, water from the bubble penetrates into the surrounding ground thus increasing the pore pressure there also.

In the far field, the increase in pore pressure is not as high as in the near field. Upto a certain distance, the deformations encountered with the wave front are mainly inelastic. The soil tends to contract because of its low density, which is prevented by the low permeability resulting in a pore pressure increase. The latter can be calculated with the aid of hypoplastic constitutive relations. The region further away from the explosion is excited by several waves of lower amplitudes resulting in small amplitude cyclic shear. The soil reaction with pore pressure increase is principally the same as with more familiar technics of dynamic compaction.

Soil Compaction

One is tempted to consider the subsequent consolidation and pore pressure dissipation by means of the classical theory of Terzaghi and Fröhlich. Kolymbas [8] has shown that this concept is misleading: it does not explain the strong densification and the rather short time of dissipation. Instead, Kolymbas has proposed a travelling discontinuity: this front is characterised by a temporary transition of the grain skeleton into a suspension which in turn settles into a more compacted state. The speed of the front is governed by permeability and compaction volume.

These considerations shed new light on methods of dynamic compaction and the so called liquification of granular masses. One can think of several novel methods of compaction when the familiar concept of consolidation is given up. Liquification is no more just a reduction of shear strength, but a mechanical instability connected with travelling segregation fronts.

FIELD TEST

Ground Conditions

The site chosen for the test was a refilled lignite mine near Senftenberg in East Germany. A simplified soil profile through this field is shown in figure 1. It consists of three fill layers having a total depth of 45 m. The top two layers consist mainly of very loosely deposited fine and medium sands. Static cone penetrometer results showed a tip resistance of only 2.0 to 3.0 MPa. Layer III has some content of fine cohesive material besides the sandy part. Static cone penetrometer results showed a resistance of about 5.0 MPa. The three layers were seperated by very compact working planes due to the compaction effect of the heavy machinery used earlier. The bottom of the mine was at a depth of 45.0 m below the ground level. The ground water table was at a depth of 5.7 m.

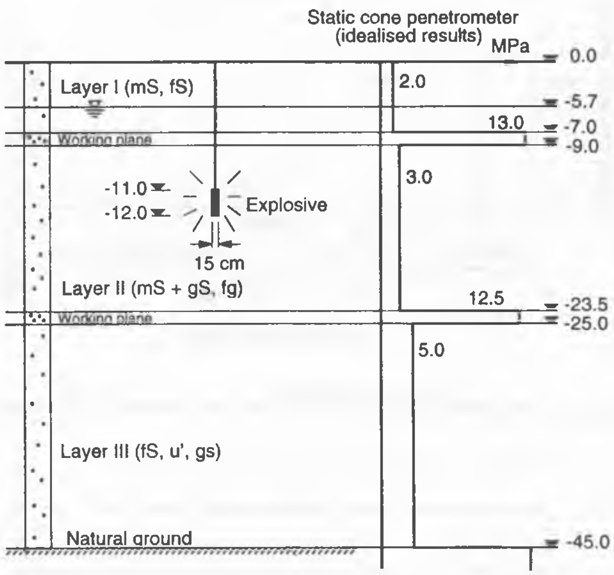

Figure 1: A section through the test field

Layout and Measurement Techniques

The explosive was placed in the second layer at a depth of 11.5 m below the ground level. The explosive used was 15 kg of Gelamon which was packed in a plastic tube having a diameter of 15 cm and a length of 1.0 m. For the placement of the explosive a borehole supported by bentonite suspension was drilled upto a depth of 12.0 m. The explosive was then lowered into the borehole. Following this, the bentonite suspension was carefully replaced with water and the borehole was filled with fine sand so as to restore the original conditions. Figure 1 shows the location of the explosive.

Prior to the placement of the explosive, the test field was extensively instrumented to measure the various physical quantitities of interest. To measure the degree and extent of liquification following the blast, 13 pore pressure gauges were placed at various radial distances from the explosive and at various depths. These gauges were pushed into the ground upto the desired depth. To study the propagation of the shock wave, 8 shock gauges (very robust acceleration gauges) were placed at 1.0 m intervals from the explosive. Particle velocities were measured in the ground using 3 component geophones at radial distances of 8, 16, 32 and 64 m at the level of the explosive and on the ground surface. The compaction effect due to the blast was studied using static cone penetrometer tests carried out before and after (14 days later) the blast. These tests were carried out at various distances from the blast point upto a maximum distance of 24 m from the blast point. Further details and the exact layout are reported in [3].

Observations and Measured Results

The blast test was carried out on the 10th of July, 1992. Immediately after the explosion (within seconds), a heave of the ground surface was observed and was measured to be about 20 cm. Following this, immediate settlements of 70 cm were observed. About 1.5 hours after the explosion, a crater began to develop and it attained its full size within an hour's time.

Settlements and cracks

Levelling mesurements were carried out 1 hour, 3 hours and 5 days after the blast. Figure 2 shows the results of these measurements carried out along the east-west axis. A maximum settlement of 1.3 m was observed (disregarding the crater). The settlement trough had a radius of about 25 m and a settlement equal to 50 % of the maximum settlement was observed at a radius of 9 m. No significant difference was observed between the measurements after 1 hour and 3 hours indicating that the major portion of the settlements took place within the first hour after the blast. The total reduction in volume due to the formation of the settlement trough was estimated to be 700 m^3.

The crater had a maximum depth of 2.1 m in addition to the that of the settlement trough. The area of the crater was about 44 m^2 and had a volume of 66 m^3.

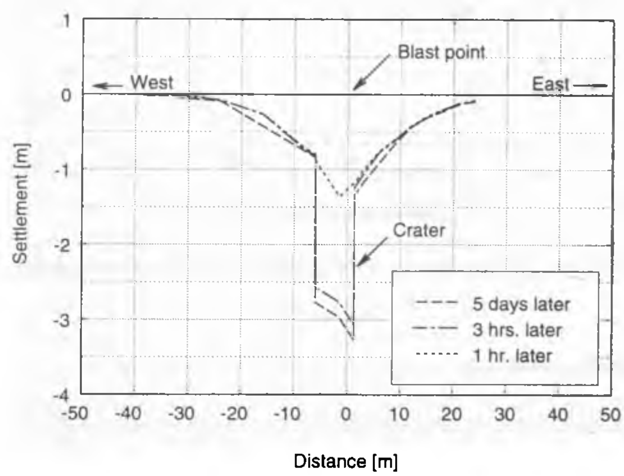

Figure 2: Measured settlements following the blast

Cracks were observed on the ground surface at various distances from the blast point. Small cracks with openings between 0 and 5 mm were observed upto distances of 32 m from the blast point. Cracks with openings larger than 5 mm and differential settlements of upto 10 cm were seen at a distance of 20 m.

Pore water pressures

The pore pressure gauges reacted immediately (within seconds) to the blast and a maximum value was attained in all gauges within 20 seconds. The excess pore water pressures were completely dissipated after 25 minutes.

Figure 3 shows the maximum pore water pressures measured as a function of depth, at a distance of 8 m from the blast point. This graph also shows the total vertical stress so as to provide an idea of the degree of liquification. It is clear that the degree of liquification is greater in the region below the explosive than above. Nearly 100 % liquification was observed at a depth of 17.5 m below the ground level.

Figure 4 shows the maximum pore water pressures as a function of distance from the blast point (at a depth of 11.5 m which was the depth of the explosive). Also shown is the total vertical stress. A 50 % liquification was observed at a distance of 15 m. At a distance of 32 m, the pore pressure rise was very small and at a distance of 64 m negligible.

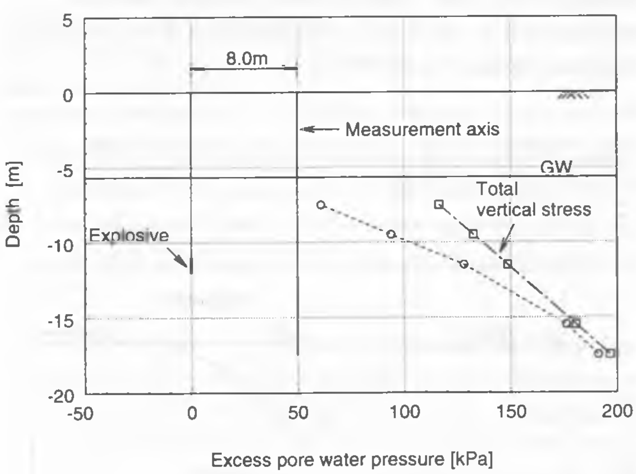

Figure 3: Maximum pore water pressures as a function of depth

Shock waves

All eight shock gauges including the one mounted on the explosive functioned during and after the blast. These gauges served to measure the exact time of the blast and the arrival of the shock wave at each of the gauges. Figure 5 shows the distance-time plot.

In the immediate neighbourhood (radial distance of 2 to 3 m), a shock wave velocity of 1754 m/s was measured. Beyond this point, the wave velocity reduced to about 473 m/s which corresponds to a P-wave and elastic deformations. A further reduction to 330 m/s was observed above the ground water table.

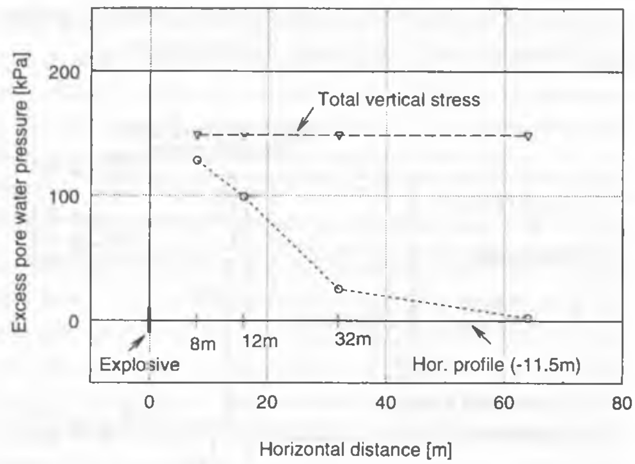

Figure 4: Maximum pore water pressures as a function of distance

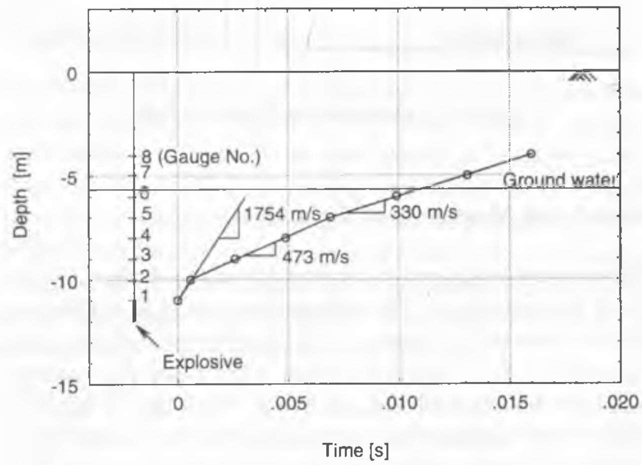

Figure 5: Wave velocities measured using the shock gauges

Particle velocities

The particle velocities measured clearly showed the arrival of the P-wave and the S-wave. The maximum particle velocities in the vertical direction is shown in figure 6. Maximum velocities of upto 260 mm/s were observed in the vertical direction at a distance of 8 m from the explosive and a depth of 11.5 m below the ground level. On the ground level, the maximum velocity was measured to be about 200 mm/s. The maximum radial components were about 10 % less than the vertical components. At a distance of 64 m, the peak values were in the range of 4-12 mm/s. In the neighbourhood of the explosive (radius less than 16 m), the underground particle velocities were greater than those at the ground level. On the other hand, in the far field (radius greater than 16 m) the surface particle velocities were larger.

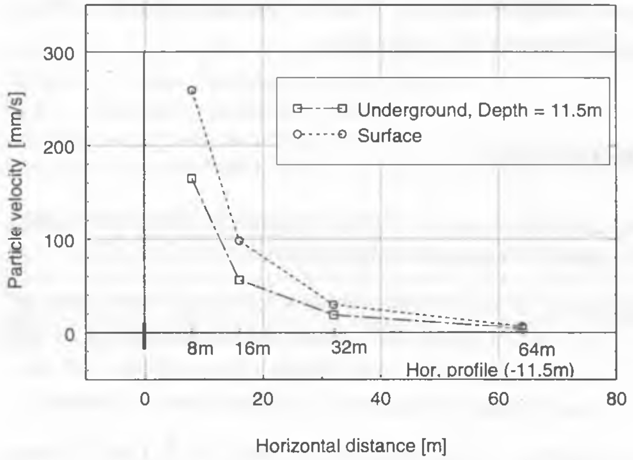

Figure 6: Peak values of the particle velocities

Static cone penetration

Figure 7 shows the results of static cone penetrometer tests carried out before and after the blast at a distance of 6 m from the blast point. The shaded region shows the increase in tip resistance after the blast. An increase in tip resistance of upto a factor of 3.0 (from 2.0 MPa to 6.0 MPa) can be observed.

INTERPRETATION

Soil Movements

One of the main effects of filling up the bore hole after placement of the explosive is that the effectiveness of the blast in terms of the compaction effect is significantly increased. A settlement trough having a volume of 700 m^3 was almost twice as big as that for an open bore hole [6]. However, the question is, wether this volume is purely due to compaction or due to displacement of the soil mass.

Assuming that the soil was compacted from its state of minimum density to a state of maximum density (e_{min} was measured to be 0.6 and e_{max} was measured to be 0.87 for the sand at the test site), the maximum possible settlement as a result of compaction is:

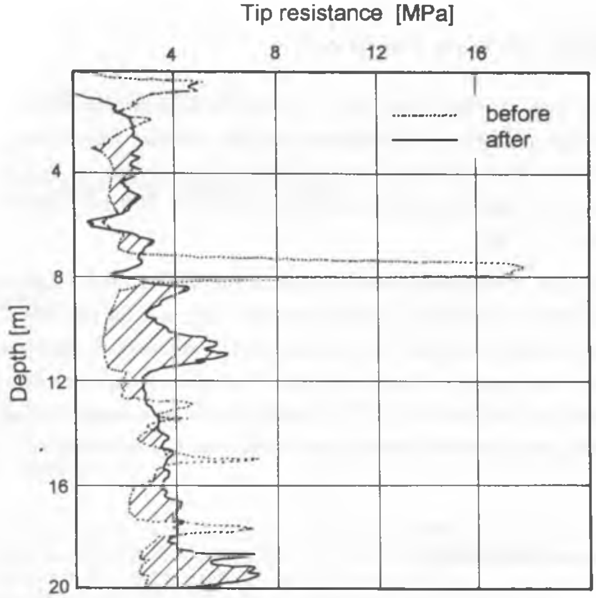

Figure 7: Results of static cone penetrometer tests (before and after the blast)

$$\Delta h = \frac{e_{max} - e_{min}}{1 + e_{max}} \cdot h_0 \tag{1}$$

where h_0 is the initial height. Assuming a h_0 of 14.5 m (the compacted region between the two working planes), $\Delta h = 2.1$ m. Considering the fact that a maximum settlement of 1.3 m (disregarding the crater) was measured, one can conclude that the main effect of the blast was that of compacting the soil.

The crater is definitely a result of the formation of the suspension bubble which travelled upwards at a speed of approximately 5 m per hour. Making the reasonable assumption that the volume of the crater is equal to the volume of the bubble, its radius is estimated to be about 2.5 m. This compares fairly well with the range of the shock wave (Fig. 5).

Pore Water Pressures

The measurements show that the region having excess pore water pressures had the shape of a pear, i.e. a larger diameter at the bottom and a smaller diameter at the top. The degree of liquification in the region above the explosive (nearer to the ground surface) was small. On the other hand, almost 100 % liquification was observed below the explosive upto a measured depth of 17.5 m. This is due to the fact that the excess pore water pressures could easily dissipate near the ground surface. The extent of the region with excess pore water pressures (about 30 m) is also an indicator of the region of influence of the blast. This agrees well with the observed radius of the settlement trough of 25 m.

Particle and Wave Velocities

The hypothesis that there exists a shock wave which travels with very high velocities, is accompanied by large plastic deformations and which dies out after a certain distance was confirmed by the shock wave measurements showing a velocity of 1754 m/s upto a radius of 2.5 m.

The particle velocities in the vicinity of the blast indicate strains of the order of 2.8×10^{-3} which is greater than that for the elastic range of loose sands [2]. The development of excess pore pressures within this region is thus consistent. Beyond a distance of 32m, strains (of the order of 10^{-4}) lie within the elastic range so that neither pore pressure increase nor compaction can be expected.

Compaction effect

The observed settlement trough clearly indicates a compaction. Penetration sounding shows a rather moderate increase of soil resistance (Fig. 7). One has to however keep in mind, that there is no direct correspondence between tip resistance and soil density.

Other techniques for the measurement of soil density are being tested. One technique is the use of a pneumatic bore hole hammer (called earth rocket). In a first field test this device has shown a marked difference in penetration speed in regions with and without compaction. Another method is based on the substantial increase of shear wave velocity with densification. Cross hole measurements with freezing in order to produce a better coupling between the excitor and the soft ground are being tested. For comparison, other geophysical methods will also be tested in the same field.

CONCLUDING REMARKS

Blasting is the only economically feasible method of compacting the very large areas of loose saturated sand deposits arising out of mining activities in the Lausitz region. The field test reported here represents a detailed study of the various phases during and after the blast. Special gauges developed for the test allowed measurements to be made very close to the explosive.

The existence of a shock wave was confirmed and its velocity was measured to be 1754 m/s. Pore pressure measurements helped to clearly observe the shape and size of the liquified region. Particle velocity measurements were used to estimate the shear strain levels induced in the soil at various distances. Levelling measurements showed the size of the compacted region and the static cone penetrometer results indicated a compaction effect. The formation of a suspension bubble which is formed by the blast was confirmed and its radius was estimated to be about 2.5 m.

Further field studies are being carried out with an aim to study the effectiveness of multiple point blasting. First tests have shown that this technique produces a higher degree of compaction and results in a larger area of compaction.

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REFERENCES

[1] Dembicki, E. et. al. (1988). Dynamische Bodenverfestigung durch Tiefensprengungen, *Bautechnik* 65:10.

[2] Dobry, R. et. al. (1982). Prediction of pore water pressure buildup and liquefaction of sands during earthquakes by the cyclic strain method. *NBS Building Science Series 138*, National Bureau of Standards, U.S. Department of Commerce.

[3] Gudehus, G., Kolymbas, D. and Raju, V. R. (1992). Sanierung und Sicherung setzungsfließgefährdeter Kippen und Kippenböschungen, *Bericht zum 1. Untersuchungsabschnitt*, Institut für Boden und Felsmechanik, Universität Karlsruhe, Karlsruhe, Germany.

[4] Henning, D. (1991). Zur Altlastenproblematik im Lausitzer Braunkohlenrevier. *Neue Bergbautechnik*. Heft 12: 417-420.

[5] Ivanov, P. L. (1983). Compaction of noncohesive soils through blasting (Russian). Moskau. "Nedra".

[6] Keßler, J. and Förster, W. (1992). Sprengverdichtung zur Verbesserung von setzungsfließgefährdeten Kippen. *Freiberger Forschungshefte*, A 819.

[7] Kolymbas, D. (1992). Sprengungen im Boden. *Bautechnik*, 69, Heft 8: 424-431.

[8] Kolymbas, D. (1992). Dynamic consolidation of soil by means of consolidation waves. Submitted for publication to *Mechanics of Materials*.

[9] Nowacki, W. K. and Raniecki, B. (1987). Theoretical analysis of dynamic compacting of soil around a spherical source of explosion. *Arch. Mech.*, 39,4: 359-384.