



Europäisches Patentamt
European Patent Office
Office européen des brevets



(11) **EP 1 029 151 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention
of the grant of the patent:
18.12.2002 Bulletin 2002/51

(51) Int Cl.7: **E21C 37/18**, E21B 7/15,
F42D 3/04

(21) Application number: **98954841.7**

(86) International application number:
PCT/NL98/00642

(22) Date of filing: **06.11.1998**

(87) International publication number:
WO 99/024694 (20.05.1999 Gazette 1999/20)

(54) **METHOD AND DEVICE FOR CRUSHING ROCK**

VERFAHREN UND VORRICHTUNG ZUM ZERKLEINERN VON GESTEIN

PROCEDE ET DISPOSITIF DE CONCASSAGE DE ROCHE

(84) Designated Contracting States:
**AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU
MC NL PT SE**

(30) Priority: **06.11.1997 NL 1007467**

(43) Date of publication of application:
23.08.2000 Bulletin 2000/34

(73) Proprietors:
• **Baggermaatschappij Boskalis B.V.**
3350 AA Papendrecht (NL)
• **Ballast Nedam Baggeren B.V.**
3700 AC Zeist (NL)
• **HOLLANDSCHE AANNEMING MAATSCHAPPIJ
B.V.**
2909 LC Capelle aan der IJssel (NL)
• **VAN OORD ACZ B.V.**
4200 AL Gorinchem (NL)

(72) Inventors:
• **VLASBLOM, Willem, Jacobus**
NL-1911 SH Uitgeest (NL)
• **KOLKERT, Willem, Johannes**
NL-2622 LA Delft (NL)

(74) Representative: **Ferguson, Alexander et al**
Octrooibureau Vriesendorp & Gaade,
P.O. Box 266
2501 AW Den Haag (NL)

(56) References cited:
EP-A- 0 453 076 EP-A- 0 692 611
EP-A- 0 777 102 DE-A- 19 534 173
FR-A- 2 275 933 US-A- 3 506 076
US-A- 3 840 078 US-A- 4 762 126
US-A- 5 386 877 US-A- 5 425 570

Note: Within nine months from the publication of the mention of the grant of the European patent, any person may give notice to the European Patent Office of opposition to the European patent granted. Notice of opposition shall be filed in a written reasoned statement. It shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

EP 1 029 151 B1

Description

[0001] The present invention relates to a method of under-water dredging, comprising the step of crushing rock, such as for instance concrete.

[0002] The costs of a dredging project may rise high as a result of a small volume percentage of rock, because the device used is unsuitable for dredging this material. Additionally it is not always possible to use explosives. There is a need for a method or device or assembly with which rock can be turned into small pieces in an efficient manner.

[0003] According to one aspect of the present invention a method of under-water dredging is provided comprising the step of crushing rock, wherein a shock wave is generated a preprogrammed form, strength and length of time for crushing said rock. Because the shock wave is given such a preprogrammed form, strength and length of time, the crushing of rock produces a desired size of pieces, and/or the crushing of rock takes place over a desired surface of the rock and/or the crushing of rock takes place up to a desired depth in the rock.

[0004] In a preferred embodiment of the method according to the invention, such a method is applied repetitively on different locations in or with regard to the rock, in vertical sense and/or in horizontal sense. By repetitively using the method on different locations of the rock an extensive area of rock can be crushed.

[0005] Preferably this comprises the step of bringing an electric wire conductor in the proximity of the rock, and having it exploded by means of supplying a pulse-shaped electric energy.

[0006] As for instance a piece of filamentary electric conductor explodes again and again it is preferred, in order to obtain a continuous process, to have non-exploded parts explode one after the other during bringing the conductor in the proximity of the rock, in other words supplying new conductor again and again.

[0007] When the rock consists of several layers of rock with separation layers in between them, the shock wave preferably has such a preprogrammed form, strength and length of time that the crushing of rock is enhanced by reflections of the shock wave due to the separation layers.

[0008] Further embodiments are described in the attached claims, the contents of which should be deemed inserted here.

[0009] Some embodiments of the present invention will be described only by way of example on the basis of the drawing, in which:

Figure 1 shows a schematical view of the soil constitution of a sea bed,

Figure 2 schematically shows the working pattern of a suction mouth of a dredging device,

Figure 3 schematically shows the propagation of a simplified shock wave,

Figure 4 shows the yield surface according to the Von Mises criterion (A) and the Mohr-Coulomb criterion (B) in the tension space,

Figure 5 shows the failure curve,

Figure 6 shows the basic model for the two-dimensional rotation-symmetrical simulations,

Figure 7 shows the set-up of the two-dimensional rotation-symmetrical simulations,

Figure 8A up to and including 8P show the effect of the shock wave on the rock and the gravel,

Figure 9 show the areas where the rock fails, the failure pattern,

Figure 10 shows the energy plot of the basic model,

Figure 11A and 11B show the influence of the radius of the load,

Figure 12A, 12B and 12C show the influence of the choice of grid,

Figure 13A up to and including 13G show the influence of the thickness of the rock layer, and

Figure 14A, 14B and 14C show the influence of the composition of the rock.

[0010] The present invention will by way of example be described on the basis of a rock layer of 0.1 m, which is

imbedded in gravel, which has to be crushed to pieces of a diameter smaller than 0.1 m. To that end the inventive method is used, with which by means of an electric pulse a shock wave is generated. With each shock wave an area of a diameter of 0.5 m has to be crushed. It will however be clear that the present invention can also be used in other fields, such as for instance the clearing of under-water concrete structures.

[0011] This example is used to give an impression of what kind of shock wave (course of pressure in time, location of the load) is necessary to crush the rock layer in an efficient manner.

[0012] Before a discussion of the propagation of the wave is at issue, an estimate of the quantity of energy necessary for disintegrating the rock will be given first. For the sake of convenience the manner in which it is disintegrated is left aside.

[0013] The specific energy, the energy necessary to disintegrate 1 m³ of rock, can be estimated by determining the fracture labour. This is equal to the so-called fracture toughness multiplied by the increase of the fracture surface. The fracture toughness, the energy necessary to create a fracture surface, is the characteristic which can be determined by means of material inspection. The increase in the fracture surface is half the sum of the surface of all pieces and grains that are formed. This surface can be estimated by means of the grain distribution of the crushed material.

[0014] By means of the theories of elastic waves, an estimate can be made of the efficiency of a one-dimensional elastic wave when it reaches a water-rock boundary surface. One part of the wave will be reflected, the rest will enter the rock layer. The difference in impedance (density multiplied by velocity of sound) between both materials is normative here.

[0015] Both the strength and the so-called Equation Of State (the pressure as function of the density and the internal energy) of a material are of great influence on the behaviour of a shock wave in a material. The strength of the material ensures an deviation on the Equation Of State in the tension-stretch diagram. The rigidity of the material and thus the inclination in the tension-stretch diagram in combination with the density is determinative for the velocity of propagation of a shock wave.

[0016] Both the failure behaviour and the Equation Of State of rock differ from most solid materials. The yield point of rock increases with increasing pressure. This unlike metals having a constant yield point. The tensile strength of rock being low here. The Equation Of State of dry rock is strongly determined by the crashing of the internal structure above pressures which are of a higher order than the UCS. With increasing pressure the pores of the material will be pressed closed and the grains from which the material is built will rearrange. When the material is fully compressed the rigidity of the material will increase again. The rigidity of the grain material will now be determinative.

[0017] When there is water in the pores of the rock these pores cannot be pressed closed entirely: water is not as compressible as air. Whether the internal structure will partly crash is unknown. Possible further examination will have to show what the Equation Of State of (soft) rock saturated with water looks like.

[0018] In general rock may fail as a result of:

1. shearing: As soon as a tension situation arises which is situated on the yield surface, the rock will plastically deform. This is accompanied by the growth of micro cracks. If this situation persists long enough with sufficient plastic deformation, the rock will fail. In this way the strength of the material deteriorates down to a residual strength which can be compared to the strength of sand.

2. traction: Rock has a limited strength when the hydrostatic pressure is low. Below a certain negative pressure the material even has no strength at all. When the tensile strength is reached a traction crack will arise. After that the material can no longer absorb negative tensions. Shearing and pressure tensions can still be absorbed.

3. pressure: When the pressure tension will get high enough, the rock will also fail on the hydrostatic axis. The structure of the rock will crash and the rock will crumble. There is no uniform criterion at hand from the literature applicable to this crumbling. Non-porous rock will not crash until under high pressures. The calcite and/or quartz will first go through (several) crystal phase transitions.

[0019] It is not easy to determine beforehand, how a shock wave will propagate through a rock. The problem will become quite awkward when the shock wave is situated in a spacial geometry. It is still preferable to obtain some indication beforehand about the propagation, so that when used in practice there is something to go by. Because of the complexity it was chosen to calculate the propagation with the finite elements of the program AUTODYN.

[0020] One-dimensional simulations will be started with. The Mohr-Coulomb strength model is chosen to model the strength of rock in AUTODYN.

[0021] In words this strength model comes down to that at a certain hydrostatic pressure p the difference between two main tensions cannot become larger than the value of the yield point y belonging to that pressure. When the yield point is reached then a rise of the largest main tension automatically results in the other main tension rising along. The tension situation can then be found back in the failure curve at a higher pressure.

[0022] From the limited data available of the Equation Of State of dry rock without pores it follows that at pressures in the range of 0 to 2 GPa the Equation Of State can be approximated by a straight line. For that reason and because

of the lack of data of water-saturated rock the linear EOS has been chosen for. The expectation is that the water in the pores will ensure that the components from which the material is built up cooperate as parallel springs. The bulk modulus can then be calculated with the volume percentage and the bulk modulus of each separate component. The rock is now depicted as a homogeneous material with this new bulk modulus.

[0023] Of the available failure criteria only the criterion for the maximum tensile strength could be used. A maximum value of 3 MPa (traction) was chosen which may reach one of the three main tensions. Here the material fails when one of the three main tensions reaches the maximum value, or all three at once along the hydrostatic axis. After failure the material can only absorb pressure tension.

[0024] There are five areas in which as a result of a simulation of a two-dimensional situation, the so-called basis model can be expected that the rock will fail

1. Zone in which pulverization may be expected.
2. Radial cracks as seen from the crater.
3. Spalling as a result of reflection against the boundary rock-gravel.
4. Traction cracks as a result of a relaxation traction wave near the axis of symmetry.
5. Spalling as a result of reflection near the axis of symmetry.

[0025] Calibration of these simulations with experiments is necessary to prove how the rock exactly fails and which failure pattern goes with it. With the results of these simulations as only information, a maximum piece size of approximately 10 cm appears to be a safe estimate.

[0026] From the simulation of the basic model follows that with an annular load a shock wave with an energy of about 29 kJ enters the rock layer. This shock wave ensures, that spread over a diameter of approximately 0.5 m, different areas are formed within which the rock fails. Here some pieces may be formed with a maximum size of 10 cm. The rest of the material will be more finely spread.

[0027] If it is assumed that a quarter of the energy released at explosion of the wire enters the rock layer, about 120 kJ will be necessary with this method, to obtain pieces of maximal 10 cm in a rock layer which is 10 cm thick. With the crushed volume of 0.02 m³ the specific energy of this method can be estimated at 6 MJ/m³.

[0028] Besides the simulation with the basic model tests have been carried out in which the influence of the various parameters has been examined. The conclusions that can be drawn from them are:

- * An annular exploding wire is an effective manner to apply a quantity of energy over a large area in a spread way. If it is desired that an area with a radius of 25 cm fails, a loading radius of 20 cm appears to be a good choice.
- * If the layer of rock is twice as thick a hole with a radius of 20 cm in stead of 25 cm arises. If the same load is put on a half finite rock layer, a hole with a half ellipsoidal shape will arise. This hole has a diameter of about 55 cm and a maximum depth in the centre of the hole of approximately 20-25 cm.

[0029] In the description given below of a exemplary embodiment of the present invention symbols will appear regularly. In order to elucidate the understanding of these symbols a list of symbols is shown below.

List of symbols		unit
A	surface of cross-section on which F_L is active	m^2
A_{fr}	fracture surface per unit of volume	l/m
c	velocity of propagation of an elastic wave	m/s
c_1, c_2	velocity of propagation in material 1 and 2	m/s
CCS	Confined Compressive Strength	N/m^2
d	grain diameter	m
D	damage parameter	-
dl	the distance bridged in a time dt by one pulse	m
dt	the time that the force F_L is active	s
E	Elasticity modulus	N/m^2
E_0, E_1	internal energy of the material before and after the front of the shock wave	m^2/s^2
EOS	Equation Of State situation equation	-
F_L	longitudinal force active on a given cross-section	N
G	gliding modulus	N/m^2
G_{IC}	fracture toughness	N/m

(continued)

	List of symbols	unit
5	HEL Hugoniot Elastic Limit	N/m ²
	K bulk modulus	N/m ²
	K _i bulk modulus of a component of rock	N/m ²
	K _{IC} critical tension intensity factor	Nm ^{3/2}
	K _s bulk modulus of grain material	N/m ²
10	K _w bulk modulus of water	N/m ²
	K ₀ bulk modulus of the rock in drained situation or with air in the pores.	N/m ²
	m relation pressure and tensile strength of rock	-
	m the mass on which F _L is active	kg
	n porosity	-
15	p hydrostatic pressure	N/m ²
	R reflection coefficient	-
	s fracture degree of rock	-
	s material constant	-
20	SE Specific Energy	N/m ²
	t time	s
	TS Brazilian Tensile Strength	N/m ²
	u velocity of material	m/s
	UCS Unconfined Compressive Strength	N/m ²
25	V _s velocity of propagation of a shock wave	m/s
	W energy of a shock wave	N/m
	W _I energy of an incoming shock wave	N/m
	W _R , W _T energy of the reflection and transmission shock wave	N/m
30	W _{fr} fracture labour	N/m ²
	y yield point or yield	N/m ²
	y ₀ constant yield point or yield with the Von Mises criterion	N/m ²
	α _i volume percentage of a component of rock	-
	Δt duration of pulse	s
35	ε _x , ε _y , ε _z stretch in x, y and z direction	-
	γ surface tension	N/m
	μ impedance relation of two media	-
	ν lateral contraction coefficient	-
40	ρ diviatoric length in tension space	N/m ²
	ρ density	kg/m ³
	ρ ₀ total density of water saturated rock	kg/m ³
	ρ ₁ , ρ ₂ density of material 1 and 2	kg/m ³
	ρ _s , ρ _w density of grain material and water	kg/m ³
45	σ tension	N/m ²
	σ ₁ largest main tension	N/m ²
	σ _{1r} , σ _{1w} largest main tension in rock and water	N/m ²
	σ ₂ , σ ₃ the other main tensions	N/m ²
	σ _{1n} , σ _{3n} normalized largest, smallest main tension respectively	-
50	σ _{HEL} tension level of the Hugoniot Elastic Limit	N/m ²
	σ _{i,max} maximum tension on traction of one of the three main tensions	N/m ²
	σ _I tension of incoming wave	N/m ²
	σ _R tension of the reflected wave	N/m ²
55	σ _T tension of the transit wave	N/m ²
	σ _x , σ _y , σ _z tension in x, y and z direction	N/m ²
	τ _n standardized sliding tension	-

(continued)

List of symbols	unit
ξ	hydrostatic length in the tension space N/m ²

[0030] In dredging projects it occurs quite often that a part of the material to be excavated consists of rock. A dredging device which is designed for sand, gravel or clay is not always suitable for excavating this material. Also a sludge sucker comes across too a hard piece in a project that mainly consists of soft rock. In that way as a result of a small percentage of volume of (hard) rock, the costs of a project may rise high because of abnormal wear or overload of the device. Additionally it will not always be possible to use explosives in such cases, because of the high costs, the great depth of water or because it is not allowed.

[0031] A device or mounting a provision on an existing device, which in an efficient manner can crush small volumes of rock may be a useful addition to the arsenal of devices from which a dredger can choose.

[0032] Below such a device, and a new method are described in which by means of an electric pulse a shock wave is generated. With this shock wave rock can be crushed.

[0033] In an offshore mining project sediment containing minerals is won with a dredging device standing on the bed. In a diagram the build-up of the soil is as shown in figure 1.

[0034] Essential is that the gravel layers, in which the precious minerals are present, are completely removed (no spilling). Excavation, takes place with a suction mouth which can make movements like a sewing machine (vertical penetration, raising, lateral movement etc.).

[0035] Figure 2 schematically shows the method with the pattern that the suction mouth makes as seen from above. It is expected that said suction mouth will have problems penetrating the cemented layer, when one works in the conventional manner.

[0036] According to the invention a provision on the suction mouth crushes a rock layer of a thickness of 0.1 m and a pressure strength of 10 Mpa. Here it is ensured that the pieces are of a size smaller than 0.1 m. The suction mouth has a diameter of 0.5 m and can exert a force of 150 kN on the bed in all directions.

[0037] It appeared that rock can be crushed when it is hit by a shock wave. Shock waves can among others be generated by explosives. The inventive method for generating shock waves, is sending an electric pulse with a high power during a fraction of a second through a conductive wire, for instance copper or aluminium. This wire will because of its electric resistance rise so high in temperature, that it changes into gas or plasma phase. This gas will expand so fast that a shock wave is realised.

[0038] Before the propagation of the shock wave is described, first an estimate is made of the energy which is required for the disintegration of rock, the so-called fracture labour. It is left aside her in which manner disintegration takes place.

[0039] The specific energy can also be calculated. Here the fracture labour W_{fr} is determined:

$$W_{fr} = G_{IC} \times A_{fr} = 2\gamma \times A_{fr} \quad (N/m^2) \quad [2.2]$$

in which:

G_{IC} : fracture toughness (J/m²)

A_{fr} : surface of fracture per unit volume (m²/m³)

γ : surface tension (J/m²)

[0040] The fracture toughness can be calculated with:

$$G_{IC} = \frac{1-\nu^2}{E} K_{IC}^2 \quad (J/m^2) \quad [2.3]$$

Here K_{IC} is the "critical stress intensity factor", material characteristic which has to do with the critical increase in tension around a crack tip. K_{IC} can have the following values:

$K_{IC} = 0.2 - 1 \text{ MPa m}^{1/2}$ for sandstone

$K_{IC} = 1.5 - 2.7 \text{ MPa m}^{1/2}$ for granite

$K_{IC} = 0.5 \text{ MPa m}^{1/2}$ for rock with an E modulus of 4 GPa

[0041] The lateral contraction coefficient $\nu = 0.25$ and an E modulus of 4 GPa gives this with equation [2.3] :

$$G_{IC} \approx 59 \text{ J/m}^2 \text{ with } K_{IC} = 0.5 \text{ MPa}^{1/2}$$

$$G_{IC} \approx 9.4 \text{ J/m}^2 \text{ with } K_{IC} = 0.2 \text{ MPa}^{1/2}$$

[0042] For soft rock (10 MPa) which has been chosen as basic material it can be expected that the fracture toughness is low (10-20 J/m²). The fracture toughness however, depends on the velocity of deformation under which a fracture arises and will as a result of it increase. Additionally the fracture toughness will also increase as a result of water in the pores. A fracture toughness of $G_{IC} = 50 \text{ J/m}^2$ will further be assumed. This estimate has been made on the basis of very few data, completed with a number of assumptions and as a result of this only indicates the order.

[0043] The increase of the fraction surface can be calculated by taking the sum of the surface of all pieces and grains which are formed and dividing this sum by two. After all as a result of each fracture two fracture surfaces are created. In the calculation of the surface use can be made of the relation surface:volume of a grain. If a cube-shaped grain is assumed:

$$A_{fr} = \frac{1}{2} \frac{6\sqrt{3}}{d} = \frac{3\sqrt{3}}{d} \quad [2.4]$$

is valid in which:

A_{fr} : the fracture surface per cubic meter of crushed rock. (m²/m³)
 d : the grain diameter, the diagonal of the cube. (m)

[0044] By means of the grain distribution of the crushed material the total fracture surface can be determined.

[0045] Examination of the soil proved that about 65% of the rock consists of calcite particles with a grain diameter between 0.01 and 0.03 mm. Furthermore the rock consists of about 35% of quartz and other particles with a grain diameter of about 1 mm. If it assumed that the rock is completely crushed to grains with [2.4] follows:

$$A_{fr} \approx 2,5 * 10^5 \text{ m}^2/\text{m}^3.$$

[0046] With a fracture toughness of G_{IC} of 50 J/m² and an increase of the fracture surface $A_{fr} = 2,5 * 10^5 \text{ m}^2/\text{m}^3$, the fracture labour for totally crushing the examined rock material to grains according equation [2.2] will be:

$$W_{fr} \approx 13 \text{ MJ/m}^3$$

[0047] If the rock is not completely crushed to grains but large pieces are created, the fraction surface is many times smaller and less energy is necessary. When for instance rock is divided into cubes of 10 cm W_{fr} will be $\approx 3 \text{ kJ/m}^3$. This quantity of energy is negligible with respect to the energy necessary for total crushing.

[0048] Independent of the method used for disintegrating rock, the fracture labour can be estimated by multiplying the fracture labour necessary for total crushing by the volume percentage of the rock which is crushed in the process.

[0049] The intention of the method with the exploding wire is to create a hole with a diameter of 0.5 m in a rock layer of 0.1 m thick with each generated shock. The volume that has to be crushed each time will then amount to 0.02 m³. The energy necessary added to the layer of rock for total crushing will be approximately 250 kJ.

[0050] The G_{IC} can among others be determined with a "Split Hopkinson Bar Test". In this test a test piece is pulled apart hydraulically or by means of a falling weight. By determining the fracture surface which is formed and the necessary energy an estimate of G_{IC} can be made. Moreover with this test the influence of the velocity of deformation and the presence of water on the fracture toughness can be determined.

[0051] With the theories of elastic waves, an estimate can be made of the efficiency of a one-dimensional elastic wave when it reaches a water-rock boundary surface. Here it regards the theoretical case of a one-dimensional wave with a rectangular tension course. The material characteristics are chosen as follows

Table 1:

the chosen material characteristics for the calculation according to the elastic wave theories.		
	water	rock
ρ (kg/m ³)	1000	2500
c (m/s)	1500	2760
E (GPa)	2.3	19

[0052] As described above, for the energy necessary for total crushing, the order of 13 MJ/m³ followed. For a rock layer of 0.1 m thick $W_T = 1.3$ MJ/m² is valid for the energy of the transit wave right after the boundary surface water-rock. For the incoming wave would then be valid: $W_I = 2.1$ MJ/m² with

$\sigma_I = 1$ GPa and $\Delta t = 6.5 \mu s$

[0053] With table 1 then follows:

$\sigma_R = 0.64$ GPa and $\sigma_T = 1.64$ GPa

[0054] And :

$W_R = 0.8$ MJ/m² and $W_T = 1.3$ MJ/m²

As will be described later, this situation will be simulated with the program AUTODYN.

[0055] It follows that about 40% of the energy is reflected and remains in the water. So when an elastic pulse passes the boundary surface water-rock at a right angle, only 60% of the energy of said pulse enters the rock material.

[0056] The equations used here are valid for an elastic material in a one-dimensional situation. Because exactly here plastic deformation and fracture are wanted, this sum only is a part of the estimate of the order of the necessary tension, length of pulse and energy of the shock wave. The tension and the length of the pulse can be adapted without changing the supplied energy.

[0057] For a brittle material like rock it will be difficult to indicate what the load has to be for failure. This can, among others be made clear with the tension-stretch diagram with a one-axis tension situation (figure 3). The tension reaches a maximum: the UCS, but the rock can still absorb stretch after that before it has failed completely. The same goes for the one-axis deformation situation in a shock wave. When the elastic limit (HEL) has been reached, the rock starts to plastically deform and cracks will start to grow. Whether an instable situation will arise, in which the cracks keep on growing until they reach a free surface or another crack, depends on the level and the duration of the load.

[0058] Rock has a strength behaviour which can be approximated with the Mohr-Coulomb criterion (figure 4 (B)). and the Von Mises criterion (figure 4(A)).

[0059] It is not simple to determine how a shock wave will propagate through a rock. The problem will become even more difficult when the shock wave is situated in a spacial geometry. Because of the complexity it was decided to calculate the problem with an finite elements program. Such a determination will be advantageous when adjusting parameters in practical uses.

[0060] AUTODYN™ is a program (so-called "hydrocode") of Century Dynamics Inc. which has especially been designed for non-linear dynamic problems. The program is especially used for problems which strongly depend on time which are geometrically non-linear (large stretches) and in which the material behaves non-linear (plasticity and failure). These are particularly impact and penetration problems (ballistics), the simulation of explosions and the examination of shock waves in gasses, liquids and solid materials.

[0061] Both time and space are divided by AUTODYN. The time is divided in steps in time and the space into cells. Each step in time the program calculates the set of cells. The outcome of such a calculation cycle is the starting point of a next cycle.

[0062] For this problem the Lagrange processor has been chosen, so that the deformation of the rock can be followed, well.

[0063] The following actions have to be taken in setting up a new simulation:

* making grid

AUTODYN can in a simple manner divide the system, which has to be calculated, into finite elements, also called cells. AUTODYN only counts in quadrangular cells. Each cell has four nodal points and the four sides of the cell consist (also after deformation!) of straight lines. The set of cells is also called the grid.

* filling the grid with material

The cells can now be filled with a material. For each material data have to be given about the EOS, the strength criterion and the failure model. These material models are elucidated hereafter.

* initial conditions

It should be indicated what the point of departure is on $t = 0$: indication of initial velocity, tension or energy of a material.

- * indicating boundary conditions

Boundary conditions can be imposed on the sides of the cells, in which the boundary condition is constant between two indicated nodal points. Examples of boundary conditions are: a certain course of the tension in the time, velocity in x- and y-direction or transmitting tensions out of the system.

- * indicating targets

In the grid targets can be placed. These targets register the changes in the time of each wanted variable. In this way after the simulation ends the history of the various points in the system can be shown.

- * symmetry

With AUTODYN a situation can be, calculated in which the cells are infinite long in the direction perpendicular to the 2D surface. A second possibility is a rotation-symmetric situation, in which the x-axis is the axis of symmetry. In this way annular cells are created: a cell is a body of revolution with a quadrangle as surface of revolution.

[0064] AUTODYN has the possibility to model porous materials. Materials such as rock, concrete and sand contain pores, which under pressure of for instance a shock wave can crash. In the porous model the pressure can be entered lineary step by step as a function of the density. In that way the three areas of elastic compression of the intact material, compaction by failure and compression of the condensed material can be modelled.

[0065] Water-saturated rock as a result of the presence of water in the pores cannot be condensed completely. The modelling of water-saturated rock by means of the porous model therefore does not appear to be correct. Again due to the lack of data this model cannot be used.

[0066] From the limited data available on the EOS of dry rock without pores it follows that with pressures in the range from 0 to 2 GPa the EOS can be approximated by a straight line. For that reason and because of the lack of data on water-saturated rock the linear EOS has been chosen. It is expected that the water in the pores ensures that the components from which the material has been built, up cooperate like parallel springs. The rock is now presented as a homogeneous material with a new bulk modulus determined from the components from which the rock has been built up.

[0067] Experimental material examination is necessary to determine the behaviour of water-saturated rock under shock load with pressures between 0 and 2 GPa. The Plate Impact Test or the Hopkinson Bar Test could be used for this examination. complex. The three-dimensional problem is rotation-symmetric so that a two-dimensional geometry will suffice.

[0068] As described above the rock may fail on traction, by shearing and pulverization on pressure. AUTODYN has various failure models available which can model the failure behaviour:

- * Maximum traction tension of the main tensions. When one of the three main tensions exceeds the indicated traction tension the material fails and can subsequently only absorb positive tension. This criterion is suitable for modelling failure on traction of rock (see figure 5).
- * Maximum sliding tension. Above a certain indicated maximum sliding tension the material fails (see figure 5). The maximum yield point and with it the sliding tension in rock depends on the prevailing pressure. This model therefore cannot be used.
- * Maximum value of the main stretches (on traction). The rock fails when it is stretched too far in one of the directions of the main stretches. There are no direct data available for this criterion.
- * Maximum sliding stretch. The rock fails when it shears too much. Just like the sliding tension with rock it depends on the prevailing pressure and therefore cannot be used.
- * Direction depending maximum traction tension or stretch. This model is suitable for materials with direction depending characteristics (orthotrope materials).
- * Damage model depending on plastic stretch on pressure. This model calculates with a damage parameter $D=0$ for intact rock and $D_{\max} (<1)$ for failed rock. The value of D depends on the plastic stretch. The rock starts to fail as of a certain compression. The yield point and the bulk modulus decrease under the influence of D . This model is suitable for the simulation of the pulverization on pressure. However, there are no data available for a good estimate of the plastic stretch.
- * The Johnson Holmquist model. This model also works with a damage parameter. For $D=0$ a failure curve is valid as with the Mohr-Coulomb criterion. For maximal failed rock the failure curve is valid which indicates the residual strength (see figure 5). This model appears to be very suitable to simulate both failure on traction and on shearing. During this examination, however, this model was not available yet. For future simulations this model appears to be suitable.

[0069] On the basis of calculations a rock layer can apparently be crushed by a shock wave which ensured a load

with an annular geometry. Starting point is an annular wire (through which an electric pulse is sent) which explodes 2 cm above the rock layer. The ring has a radius of 20 cm.

[0070] The explosion apparently can ensure a load which is distributed over an area of 4 cm wide. The load can only be applied constantly over a width of a cell. A stepped course (see figure 6) was chosen with a maximum tension (0.7 GPa) on a radius of 20 cm.

[0071] Further starting points of the load are:

- * A triangular shape of the pressure course in the time of the shock wave. The front of the shock wave is infinite steep here.
- * The duration of the shock wave is 25μs.

[0072] The effects the shock wave has on the rock and the gravel will be discussed here in chronological order. In figures 21A up to and including P can among others be seen:

- * The course of the pressure p in the rock and the gravel, every twentyfifth step in time.
- * The course of the pressure p in the time for a number of targets.
- * The situation in which the material is: elastic, plastic or failed in one of the three directions.

[0073] As can be seen in figure 8 the tensions in the rock near the load are high. The shock wave has the shape and the intensity of the load imposed. The tension in all directions is well above the elastic limit (see pressure course target 1). Still, it is possible that on micro scale traction tensions arise along the grains or in crack tips already present. As already mentioned before the rock can fail in this way.

[0074] After 25μs the total load in the shape of a triangular pulse has been supplied to the rock layer. As of this moment traction tensions arise at the tail of the shock wave. These traction tensions arise at the edges of the location where the load of 4 cm in width has been put on. The cause of these traction tensions can clearly be seen in the (enlarged) velocity plot on step in time 50. The rock particles move away from the location of the load. The shock wave experiences a lot of resistance of the rock at the centre below the location of the load. The free rock surface does not offer that resistance. The rock particles tend to splash away. In reality this will probably happen too.

[0075] In the enlarged situation plot of step in time 50 the directions of the main tensions have also been indicated. It can clearly be seen that below the location where the load has been put on, the main tensions lie along the x- and y-axis. Here the largest main tension is directed along the x-axis. Outside the area where target 1 up to and including 9 lie the directions diverge from the x- and y-axis. The largest main tension turns from the x-axis to the y-axis. This pattern of directions can also be seen with the traction cracks which arise in this area. These will, as seen from the location where the load was on, run away radially.

[0076] After approximately 40μs the shock wave reaches the boundary with the gravel. As of this moment a part of the shock wave will continue in the gravel layer, the other part will reflect like a pulling wave. The front of the reflected part will at first fall away against the tail of the incoming shock wave. In figure 8 it can be seen in the pressure course on step in time 100 that at about 2 cm from the boundary surface the pressure has become negative. In the situation plot of said same enclosure it can be seen that on that location the tensile strength of the rock has been reached. At this location a crack will arise. The distance from the boundary surface where this is happening depends on the difference in impedance between both materials, the course of pressure of the tail of the pulse and the tensile strength. This phenomenon is also called "spalling".

[0077] In the general case of an increasing shock wave it decreases in intensity in two ways. First of all the material will plastically deform or fail. Energy of the shock wave is transformed in deformation energy. Secondly the energy of the shock wave will be distributed over an ever larger area. The latter can therefore also be called the "geometric evaporation" of a shock wave.

[0078] With an annular load the geometry of the load will however ensure a reinforcement. To the outside, away from the axis of symmetry, the intensity of the shock wave indeed decreases, but within the ring as the energy of the shock wave as it increases in the direction of the axis of symmetry, will be distributed over an ever smaller area. As a result the intensity of the shock wave increases. With an annular load geometric reinforcement therefore occurs.

[0079] Around the axis of symmetry the geometric reinforcement described above arises. On step in time 175 it can be seen that traction tensions arise. Behind the pressure wave a traction wave arises, as a result of which the rock will fail near the axis of symmetry.

[0080] The concentrated pressure wave on the axis of symmetry will partly reflect against the rock-gravel boundary surface here as well. Said reflection causes the formation of a second "spall" area.

[0081] All above-mentioned areas where it can be expected that the rock will fail are shown in figure 9.

1. Zone where pulverization can be expected. (not simulated)

2. Radial cracks as seen from the crater.
3. Spalling as a result of reflection against the boundary rock-gravel.
4. Traction cracks as a result of a traction wave near the axis of symmetry.
5. Spalling as a result of reflection near the axis of symmetry.

[0082] The main object of this examination is determining the quantity of energy necessary to crush a rock layer efficiently with a shock wave. The pieces that are realized may not be larger than 10 cm.

[0083] For an estimate of the size of the pieces with the help of the results and particularly the above described failure pattern, the important question is: How far has the rock disintegrated in the areas which according to the simulation have failed. Two extremes are possible:

1. In areas which according to the simulation have failed only some cracks have formed. The cracks run through the heart of these areas.
2. The areas where the rock has failed are completely pulverized down to the grains from which the rock was originally built up.

[0084] In the first case pieces will be formed which are larger than 10 cm. Pieces of about 15 cm appear to be possible. The hole which is formed moreover has a radius of merely 40 cm.

[0085] In the second case, taking the maximum distance between the failed areas into account, pieces of about 5 cm are possible (figure 8, situation plot step in time 275). Theoretically annular pieces could be formed. However, this does not seem to be likely. The hole that is formed has a diameter of about 55 cm.

[0086] Validation of these simulation with experiments is necessary to show how the rock fails exactly and which failure pattern goes with it. With the results of this simulation as only information, the maximum size of piece can be estimated at about 10 cm.

[0087] In the energy plot of figure 10 it can be seen that as a result of the annular load approximately 29 kJ is supplied to the rock. Furthermore it can be seen that merely 10% (± 3 kJ) goes into the gravel. In order to get 29 kJ into the rock, however, a larger quantity of energy is necessary in the wire. The energy which is released at exploding the annular wire, will, because of the shock wave which is caused, spread in all directions. Only a part of the energy will penetrate the rock layer. Half the energy has the wrong direction and will never reach the rock layer. Another part will be reflected against the boundary water-rock.

[0088] When it is assumed that a quarter of the energy released at the explosion of the wire penetrates the rock layer, about 120 kJ is necessary in this method, to obtain pieces of maximally 10 cm in a rock layer of 10 cm in thickness. Here the rock has the material characteristics as shown in figure 6. With the pulverized volume of 0.02 m³ the specific energy of this method can be estimated at:

$$SE \approx 6 \text{ MJ/m}^3$$

[0089] This value matches the estimates given above very well. Here it is then assumed that a mere 1.5 MJ/m³ enters the rock (a quarter). Experimental examinations will have to prove whether this is a correct assumption.

[0090] A shock wave with a low intensity and a long duration of pulse will have rock fail over a larger area than a shock wave with a large amplitude and a short duration of pulse. Here the intensity of the shock wave has to be well above the elastic limit of the material.

[0091] An important parameter with which the load can be changed is the radius of the exploding wire. From the results of practical tests it appears that the rock has mainly failed within a radius of 25 cm. The cause of this is the already discussed geometric reinforcement towards the axis of symmetry and the geometric evaporation outside of it. Furthermore it strikes that the rock in the area with a radius between 5 and 15 cm contains fewer cracks. This failure pattern is important in the choice of the radius of the load.

[0092] Before the simulation with the basic model was carried out, two simulations have been carried out with as deviating failure criterion a maximal traction tension in the main directions of 10 MPa in stead of 3 MPa as in the basic model. The radius of the load in one of these two simulations was 10 cm, in the other simulation 20 cm, as in the basic model. The amplitude of the load is adapted such, that at the same duration of pulse of 25 μ s, the energy supplied was about the same. A stepped load was taken here, with 1.3 GPa as highest tension (as opposed to 0.7 GPa for the load at 20 cm). In figure 11A and 11B it can clearly be seen that with a radius of load of 20 cm the rock fails less quickly as a result of a heavier failure criterion. Still the five separate areas of figure 22 can be seen here as well. At a radius of the load of 10 cm the following strikes:

* A larger crater is formed. Because of the larger intensity of the load the deformations in the surroundings of this

load are larger too.

- * Despite the heavy failure criterion the rock almost completely fails within a radius of 12-15 cm.
- * Also with this heavy failure criterion there is no reason to assume that with this radius of load the rock fails up to a radius of 25 cm.

[0093] Regarding the choice for the radius of load the following can be said:

- * At too small a choice of the radius of load, too small an area is covered.
- * At too large a radius of load there is a chance that the rock only fails in the area below the load and near the axis of symmetry. The pieces which are formed between these areas can become too large.
- * When it is desired that an area with a radius of 25 cm fails, a radius of the load of 20 cm appears to be a good choice.

[0094] Furthermore it can be stated that the annular exploding wire appears to be an effective way to apply a quantity of energy over a large area in an distributed manner.

[0095] From the tests of the basic model it follows that with the annular load a shock wave of about 29 kJ enters the rock layer. This shock wave ensures that spread over a diameter of about 0.5 m, various areas are formed within which the rock fails. Here some pieces may be formed with a maximum size of piece of 10 cm. The rest of the material will be more finely distributed.

[0096] It is estimated that about a quarter of the energy released at the explosion of the wire will penetrate the rock layer, so that with this method approximately 120 kJ is necessary, to obtain pieces of maximally 10 cm in a rock layer of 10 cm in thickness. With the crushed volume of 0.02 m³ the specific energy becomes 6 MJ/m³.

[0097] A shock wave with a low intensity and a long duration of pulse will have rock fail over a larger area than a shock wave with a large amplitude and a short duration of pulse. Here the intensity of the shock wave has to be well above the elastic limit of the material. Knowledge about the height of the elastic limit and the course of the largest main tension as function of the stretch for the one-axis deformation situation around this elastic limit, is important for the determination of the most efficient. shock wave.

[0098] An annular exploding wire is an effective way to apply a quantity of energy over a large area in a distributed manner. If it is desired that an area with a radius of 25 cm fails a radius of the load of 20 cm appears to be a good choice.

[0099] When the rock layer is twice as thick a hole with a radius of 20 cm in stead of 25 cm as in the basic model will probably be formed. When the same load as in the basic model is put on a half-infinite rock layer, a hole with a half-elliptoidic shape will be formed. This hole will have a diameter of about 55 cm and a maximal depth in the centre of the hole of about 20-25 cm.

Claims

1. Method of under-water dredging, comprising the step of crushing rock, such as for instance concrete, wherein a shock wave is generated with a preprogrammed form, strength and length of time for crushing said rock.
2. Method according to claim 1, the preprogrammed form, strength and length of time being generated by means of pulsed electric energy.
3. Method according to claim 1 or 2, in which at least one sparking plug, at least two electrodes between which discharge is generated or a wire conductor is used for generating the shock wave.
4. Method according to claim 3, in which several sparking plugs are used for generating the shock wave, the sparking plugs being excited in order.
5. Method according to any one of the preceding claims, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock produces a desired size of pieces.
6. Method according to any one of the preceding claims, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock takes place over a desired surface of the rock.
7. Method according to any one of the preceding claims, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock takes place up to a desired depth in the rock.
8. Method according to any one of the preceding claims, wherein a shock wave, is generated repetitively in different

locations placed in or with regard to the rock, in vertical sense and/or in horizontal sense.

9. Method according to any one of the preceding claims comprising bringing a wire conductor in the proximity of the rock, and having it exploded by means of supplying a pulse-shaped electric energy.

10. Method according to claim 9, in which the guide is inserted into the rock.

11. Method according to claim 9 or 10, in which a guide with the shape of a loop or at least almost an annular shape is used as the guide.

12. Method according to claim 9, 10, or 11, in which during bringing the guide in the proximity of the rock several guide parts are intermittently inserted and each time each guide part is exploded.

13. Method according to any one of the preceding claims, in which the rock consists of various layers of rock with separation layers in between them, in which the shock wave has such a preprogrammed form, strength and length of time that the crushing of rock is enhanced by reflections of the shock wave from the separation layers.

Patentansprüche

1. Verfahren zum unter Wasser Ausbaggern, umfassend den Schritt von Zerkleinern von Gestein, wie zum Beispiel Beton, wobei eine Stoßwelle mit einer vorgeprogrammierten Form, Stärke und Zeitdauer zum Zerkleinern des Gesteins erzeugt wird.

2. Verfahren nach Anspruch 1, wobei die vorprogrammierte Form, Stärke und Zeitdauer mit Hilfe von pulsierten Elektroenergie erzeugt wird.

3. Verfahren nach Anspruch 1 oder 2, wobei zumindest eine Zündkerze, zumindest zwei Elektroden, wozwischen Entladung erzeugt wird, oder ein Fadenführer zum Erzeugen der Stoßwelle benutzt wird.

4. Verfahren nach Anspruch 3, wobei verschiedene Zündkerzen zum Erzeugen der Stoßwelle benutzt werden, wobei die Zündkerzen in Ordnung angeregt werden.

5. Verfahren nach einem der vorhergehenden Ansprüche, wobei die Stoßwelle eine derartige vorprogrammierte Form, Stärke und Zeitdauer hat, daß das Zerkleinern von Gestein eine gewünschte Brockengröße ergibt.

6. Verfahren nach einem der vorhergehenden Ansprüche, wobei die Stoßwelle eine derartige vorprogrammierte Form, Stärke und Zeitdauer hat, daß das Zerkleinern von Gestein über eine gewünschte Oberfläche des Gesteins stattfindet.

7. Verfahren nach einem der vorhergehenden Ansprüche, wobei die Stoßwelle eine derartige vorprogrammierte Form, Stärke und Zeitdauer hat, daß das Zerkleinern von Gestein bis eine gewünschte Tiefe in dem Gestein stattfindet.

8. Verfahren nach einem der vorhergehenden Ansprüche, wobei eine Stoßwelle wiederholt an verschiedenen Stellen in dem oder bezüglich des Gesteins, im vertikalen und/oder horizontalen Sinne, erzeugt wird.

9. Verfahren nach einem der vorhergehenden Ansprüche, umfassend das in die Nähe des Gesteins Bringen eines Fadenführers, und durch die Zufuhr von pulsformiger Elektroenergie das Explodieren lassen hiervon.

10. Verfahren nach Anspruch 9, wobei der Führer in das Gestein eingebracht wird.

11. Verfahren nach Anspruch 9 oder 10, wobei ein Führer mit einer Schleifenform oder zumindest fast einer Ringform als Führer benutzt wird.

12. Verfahren nach Anspruch 9, 10 oder 11, wobei während dem in die Nähe des Gesteins Bringen des Führers, verschiedene Führerteile intermittierend eingelegt werden und jedesmal jedes Führerteil explodiert wird.

13. Verfahren nach einem der vorhergehenden Ansprüche, wobei das Gestein aus verschiedenen Schichten Gestein mit dazwischen Trennschichten besteht, wobei die Stoßwelle eine derartige vorprogrammierte Form, Stärke und Zeitdauer hat, daß das Zerkleinern von Gestein durch Reflexionen der Stoßwelle von den Trennschichten verstärkt wird.

5

Revendications

- 10 1. Procédé de dragage sous l'eau, comprenant l'étape consistant à concasser de la roche, tel que du béton par exemple, dans lequel il est généré une onde de choc ayant une forme, une intensité et une durée préprogrammées en vue de concasser ladite roche.
- 15 2. Procédé selon la revendication 1, dans lequel la forme, l'intensité et la durée préprogrammées sont générées au moyen d'une impulsion d'énergie électrique.
- 20 3. Procédé selon la revendication 1 ou 2, dans lequel il est utilisé au moins une bougie d'allumage, au moins deux électrodes entre lesquelles est générée une décharge ou un fil conducteur en vue de générer l'onde de choc.
- 25 4. Procédé selon la revendication 3, dans lequel il est utilisé plusieurs bougies d'allumage pour générer l'onde de choc, les bougies d'allumage étant excitées successivement.
5. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'onde de choc a une forme, une intensité et une durée préprogrammées de telle sorte que le concassage de la roche produit des morceaux de taille souhaitée.
- 30 6. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'onde de choc a une forme, une intensité et une durée préprogrammées de telle sorte que le concassage de la roche se produit sur une surface souhaitée de la roche.
- 35 7. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'onde de choc a une forme, une intensité et une durée préprogrammées de telle sorte que le concassage de la roche se produit jusqu'à une profondeur souhaitée dans la roche.
8. Procédé selon l'une quelconque des revendications précédentes, dans lequel l'onde de choc est générée de façon répétitive en différents endroits dans la roche ou relativement à celle-ci, verticalement et/ou horizontalement.
- 40 9. Procédé selon l'une quelconque des revendications précédentes, comprenant l'étape consistant à amener un fil conducteur à proximité de la roche, et à le faire exploser en délivrant une impulsion d'énergie électrique.
10. Procédé selon la revendication 9, dans lequel le guide est inséré dans la roche.
11. Procédé selon la revendication 9 ou 10, dans lequel il est utilisé comme guide un guide ayant une forme de boucle ou au moins une forme presque annulaire.
- 45 12. Procédé selon la revendication 9, 10, ou 11, dans lequel, lorsque le guide est amené à proximité de la roche, l'on insère par intermittence plusieurs parties de guide et l'on fait exploser à chaque fois chaque partie de guide.
- 50 13. Procédé selon l'une quelconque des revendications précédentes, dans lequel la roche est constituée de plusieurs couches de roche, entre lesquelles sont disposées des couches de séparation, et dans lequel l'onde de choc a une forme, une intensité et une durée préprogrammées de telle sorte que le concassage de la roche est améliorée par les réflexions de l'onde de choc sur les couches de séparation.

55

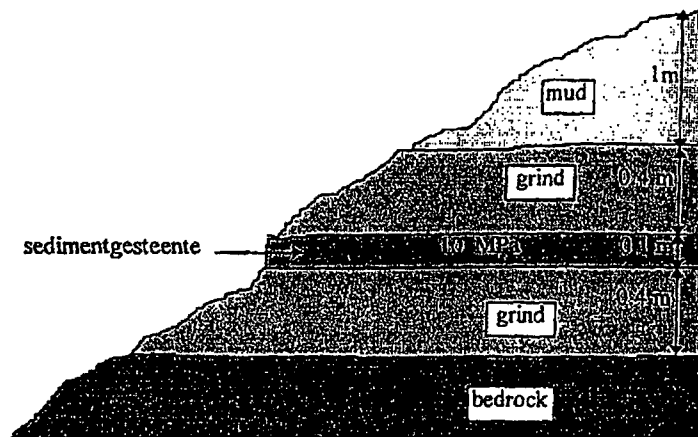


FIG. 1

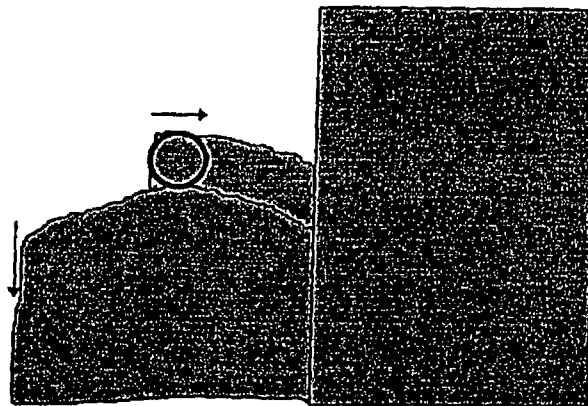


FIG. 2

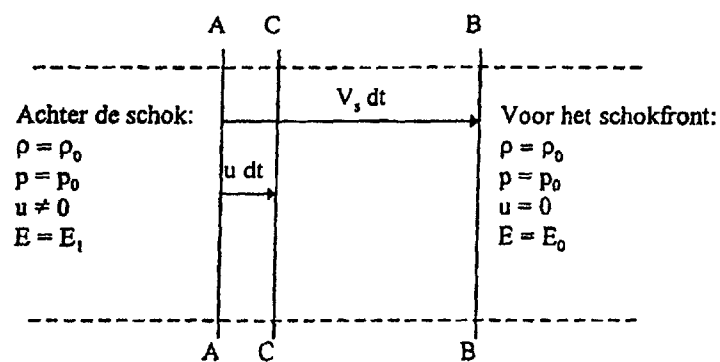


FIG. 3

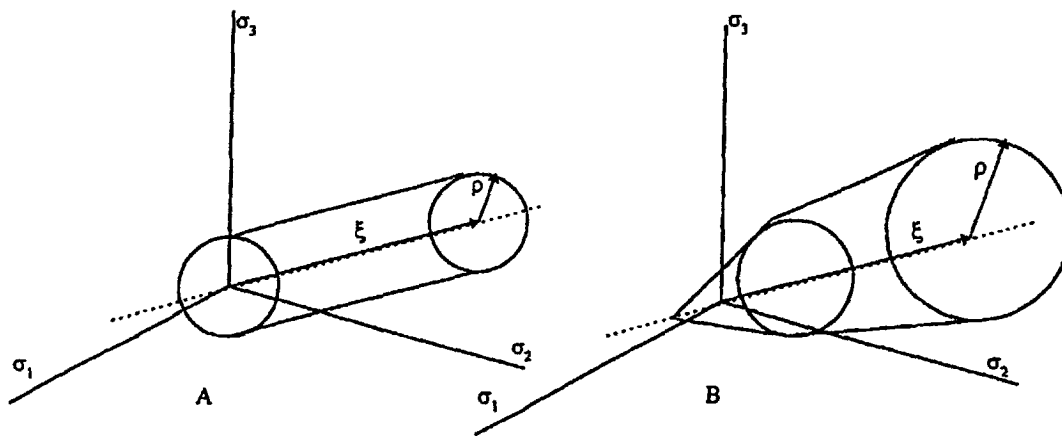


FIG. 4

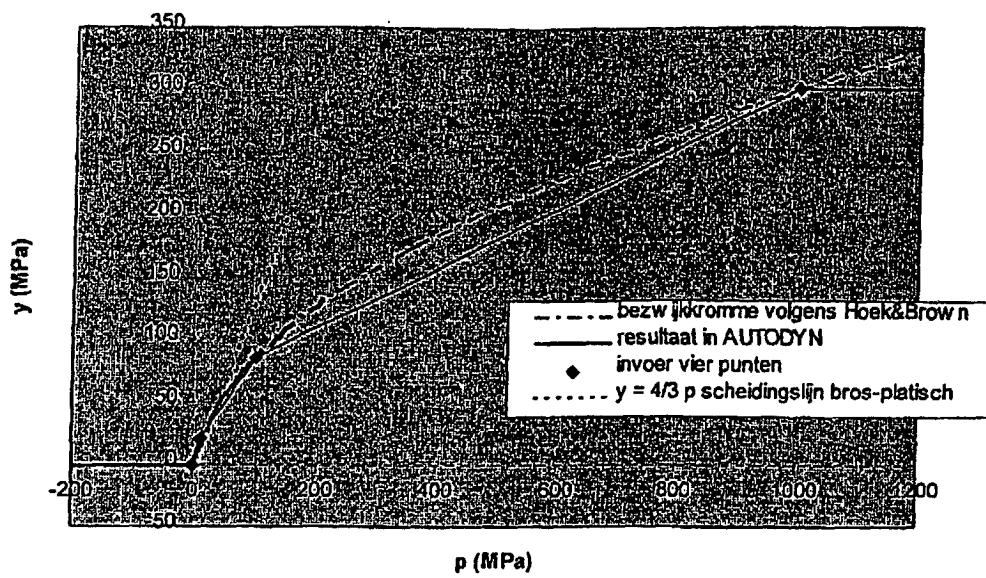


FIG. 5

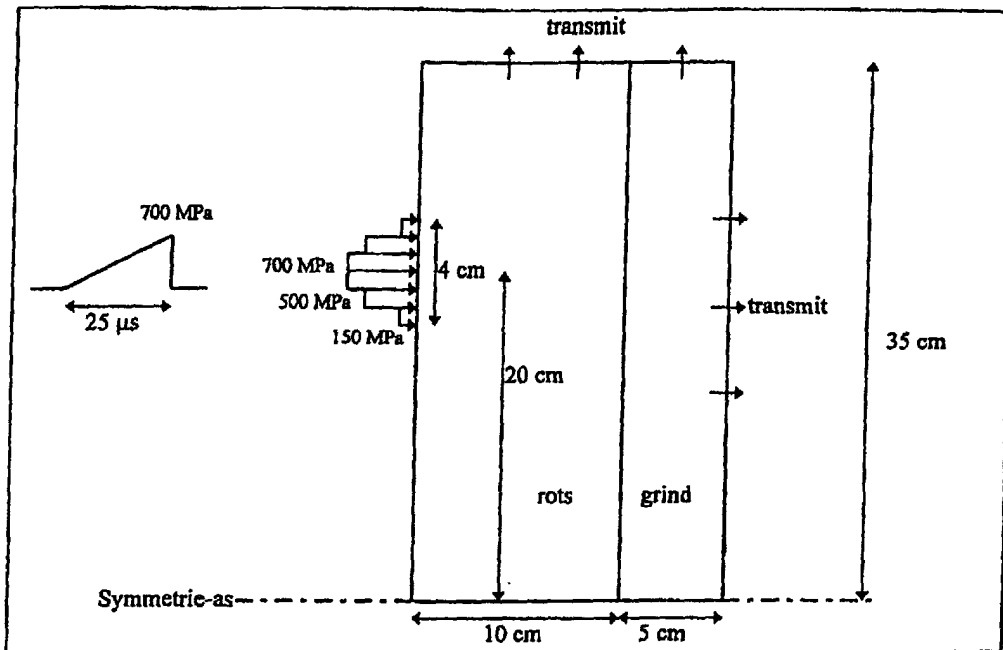


FIG. 6

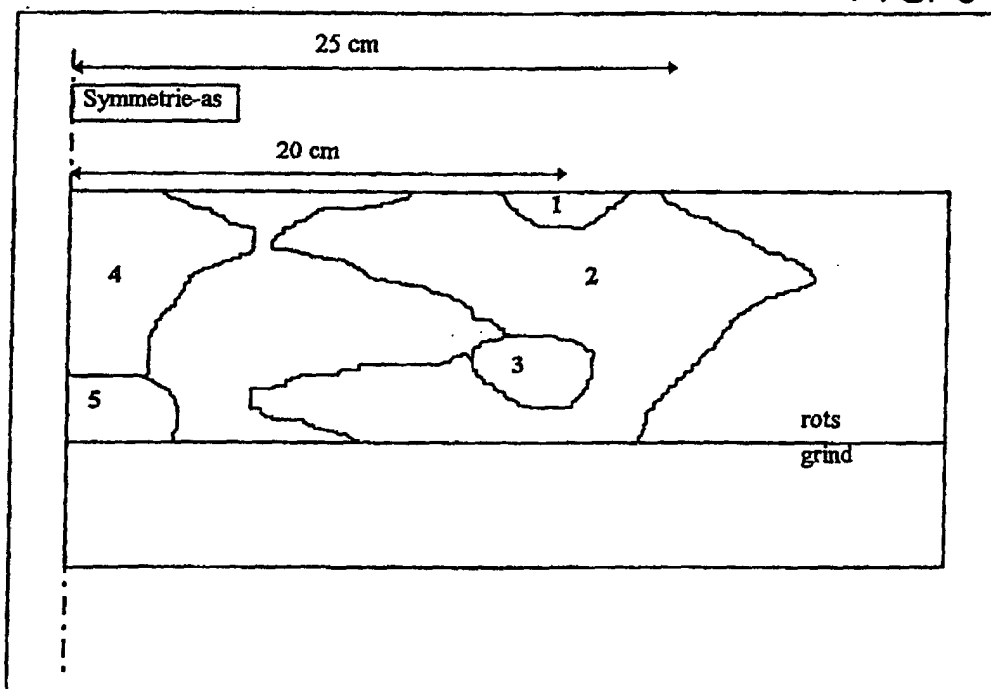
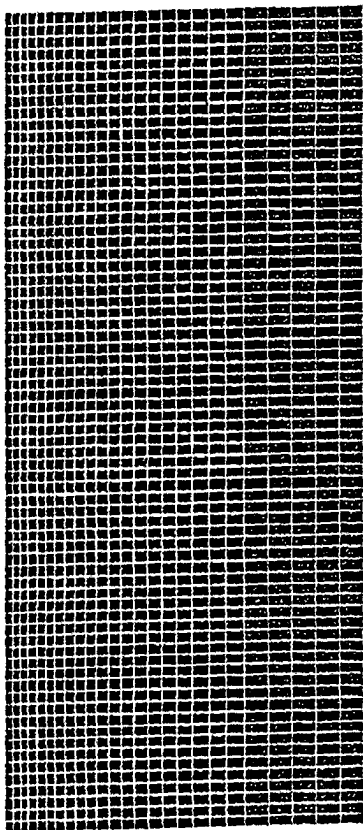
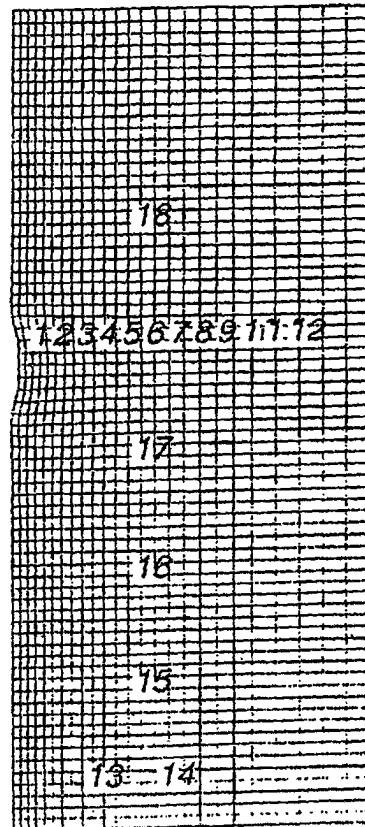
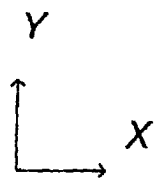


FIG. 9

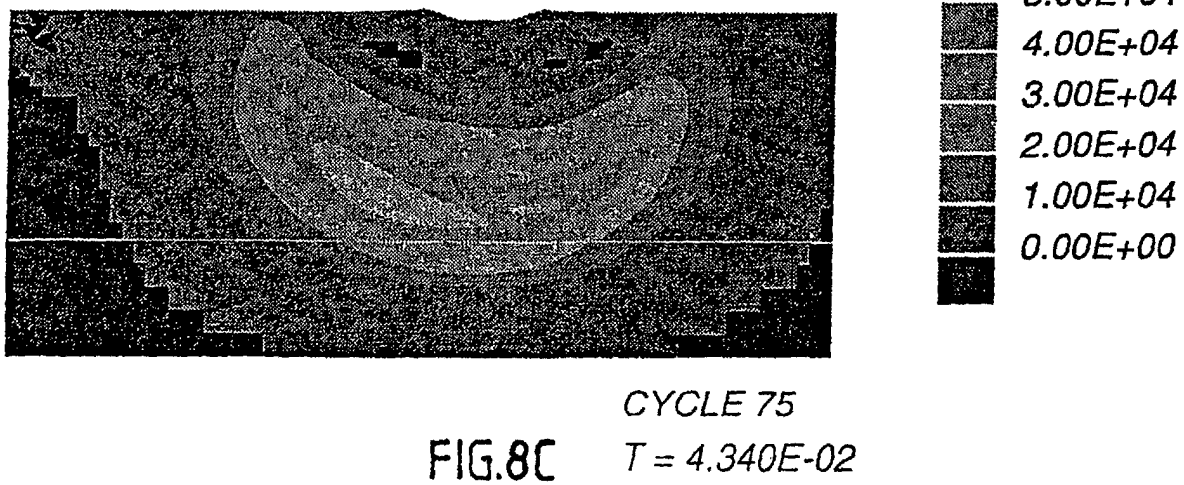
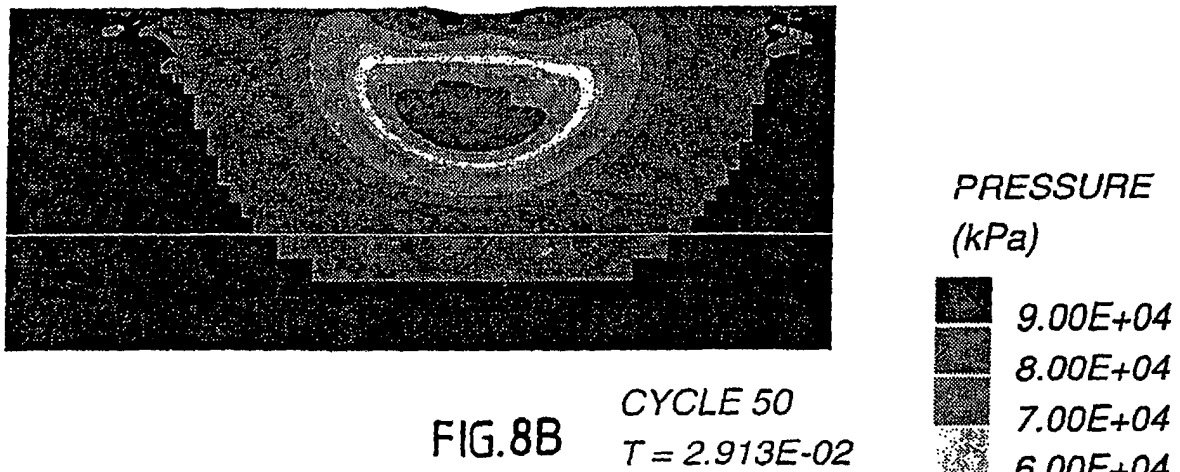
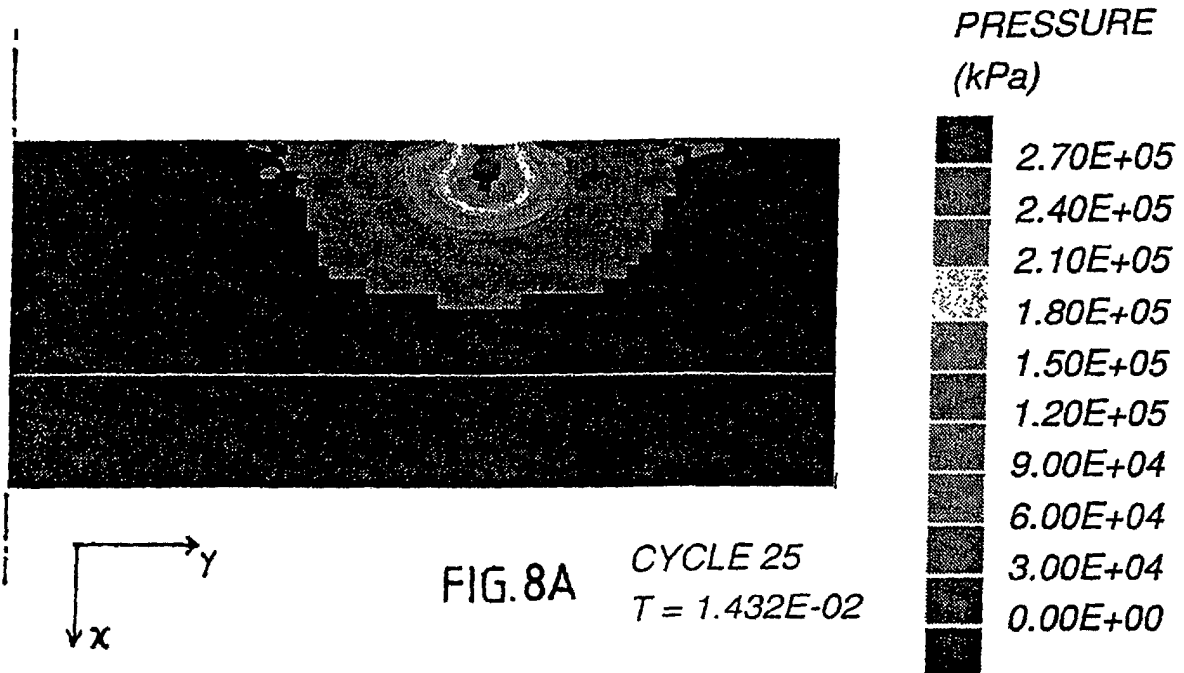


 *ROTS*
 *GRIND*



CYCLE 50
T = 2.913E-02

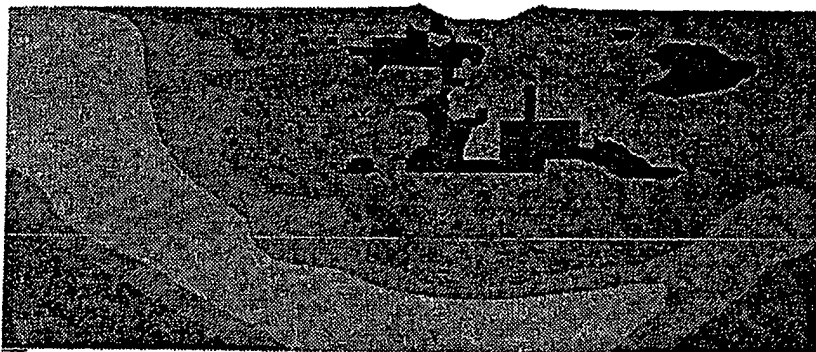
FIG. 7





CYCLE 100
 $T = 5.704E-02$

FIG. 8D



CYCLE 125
 $T = 7.022E-02$

PRESSURE
 (kPa)

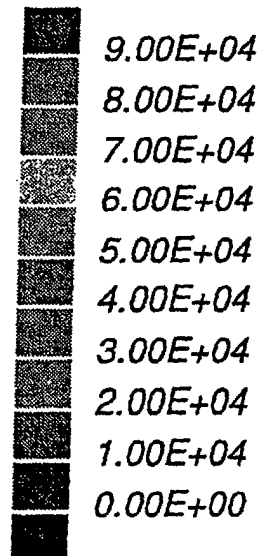
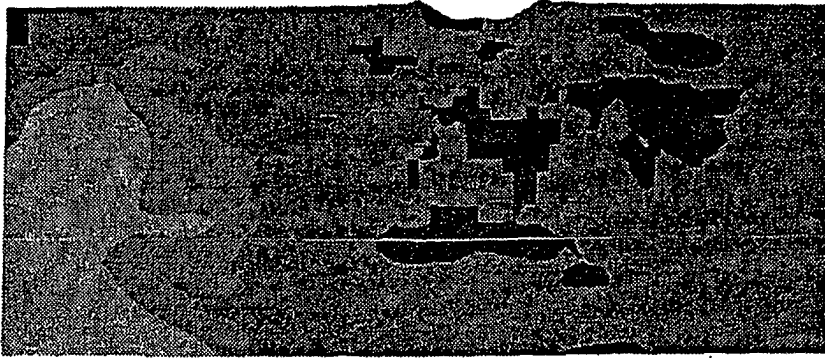


FIG. 8E



CYCLE 150
 $T = 8.316E-02$

FIG. 8F



CYCLE 175
T = 9.541E-02

FIG. 8G



CYCLE 200
T = 1.070E-01

FIG. 8H

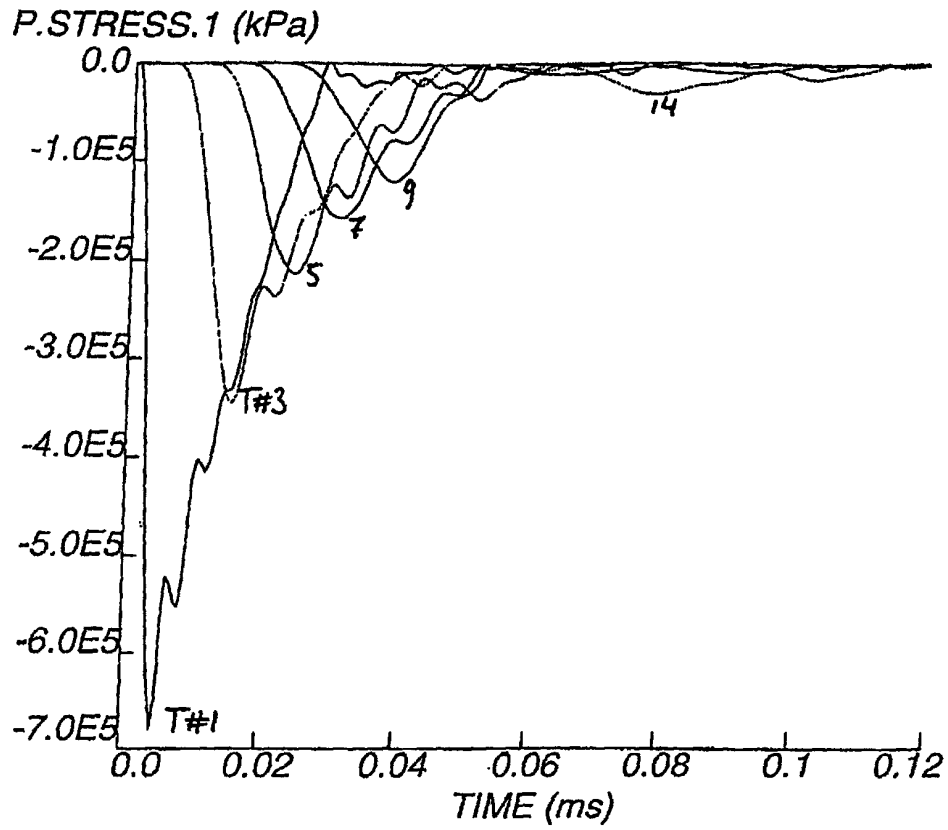


FIG. 8I

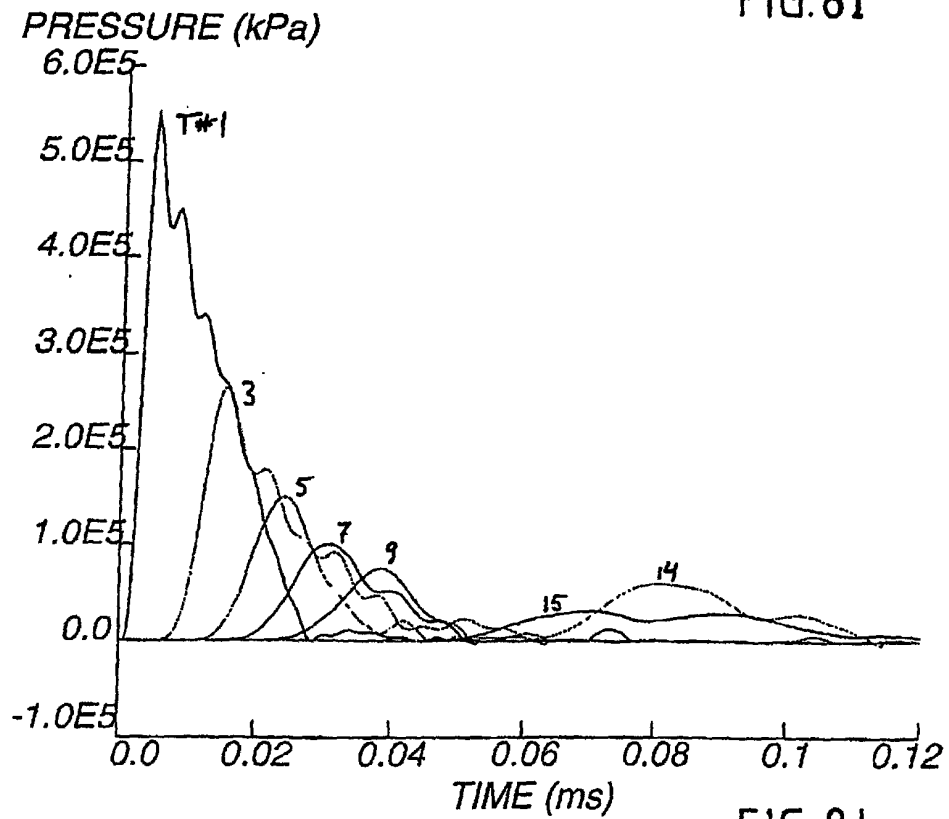
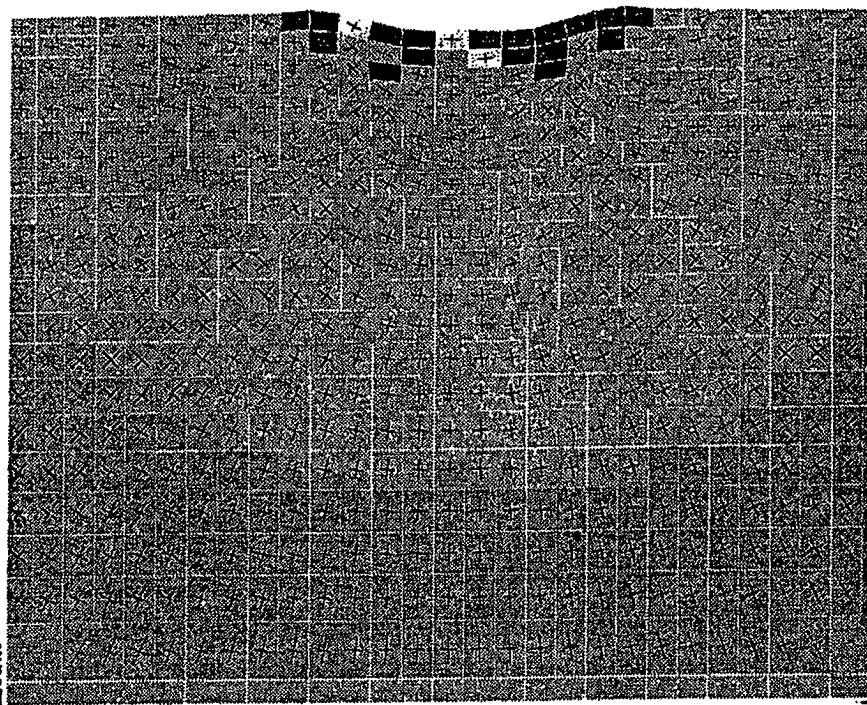


FIG. 8J



MATERIAL
STATUS

- ELASTIC
- PLASTIC
- FAILED 11
- FAILED 22
- FAILED 33

Scale
3.200E+01

FIG. 8K

CYCLE 50
 $T = 2.913E-02$

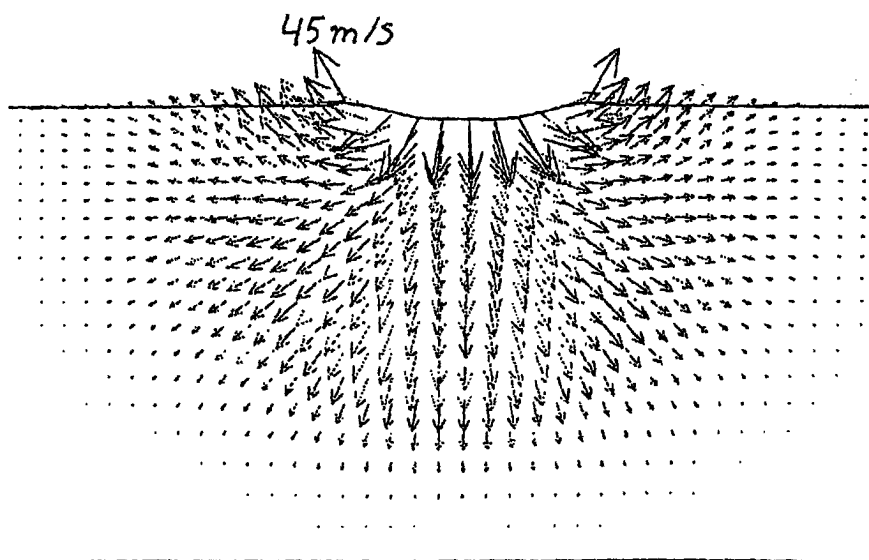
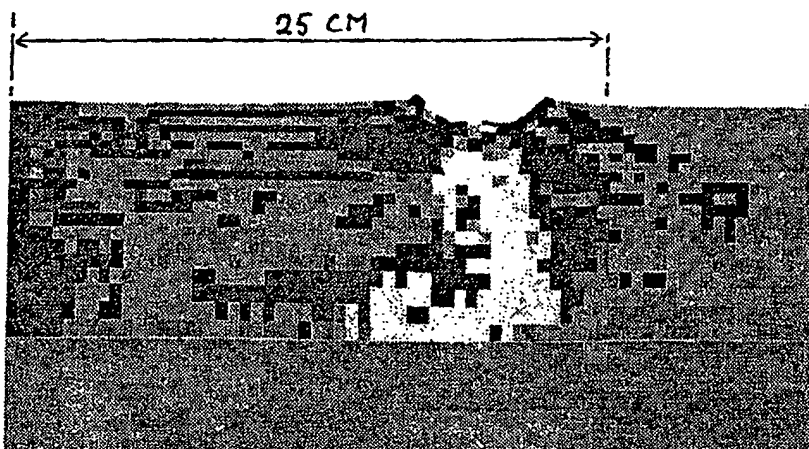
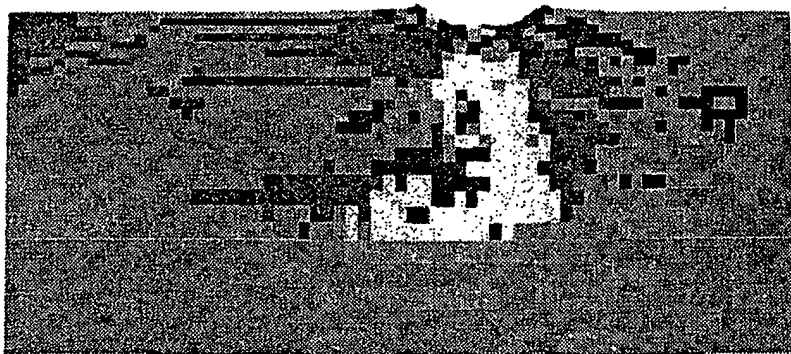
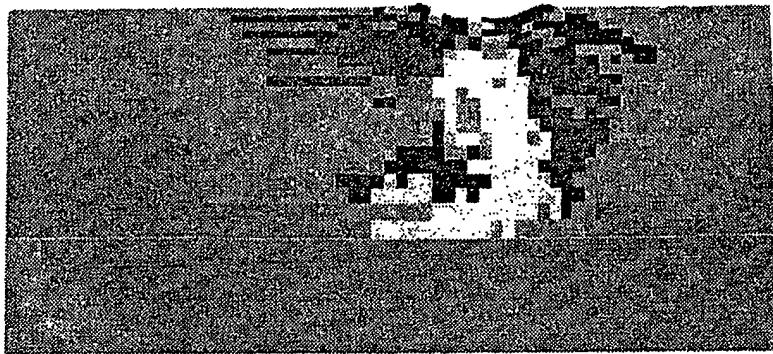
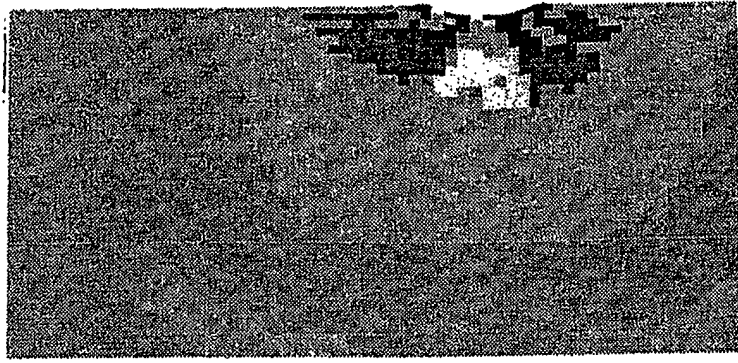


FIG. 8L



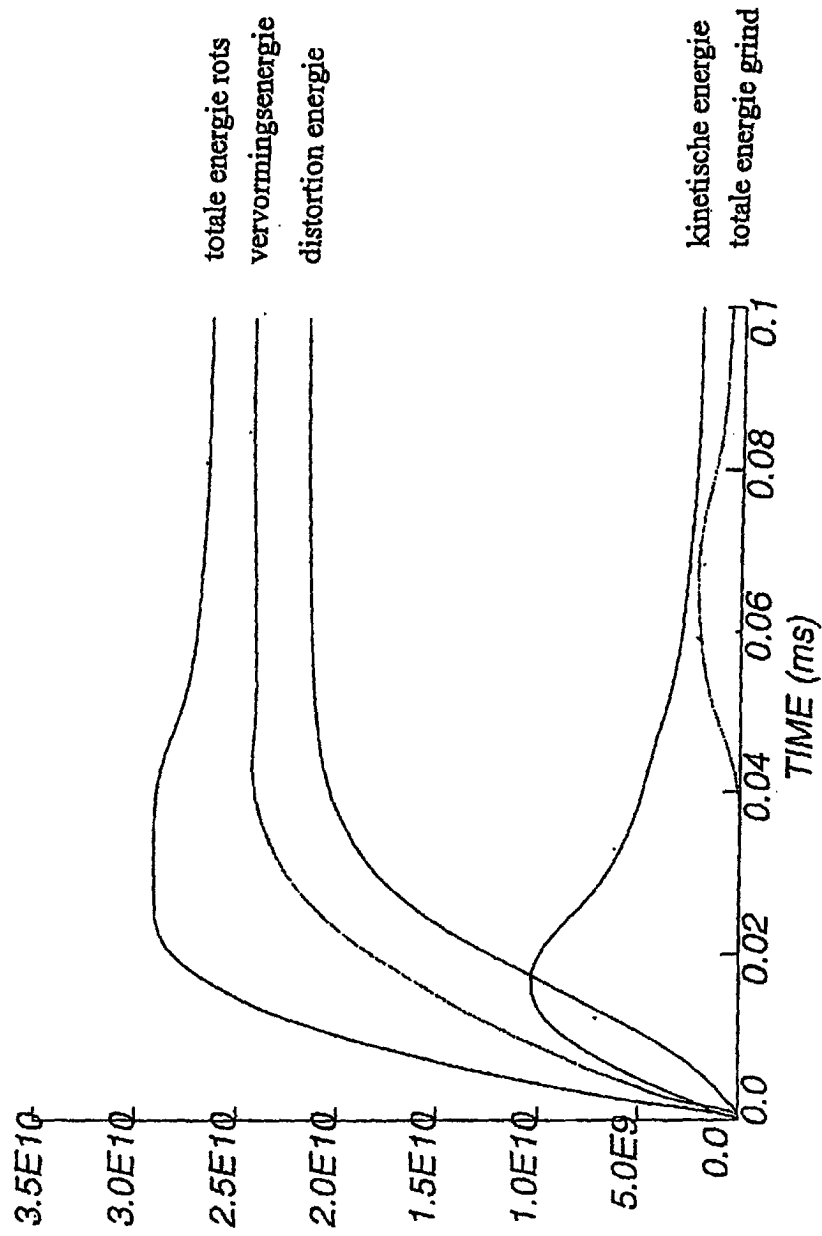


FIG. 10

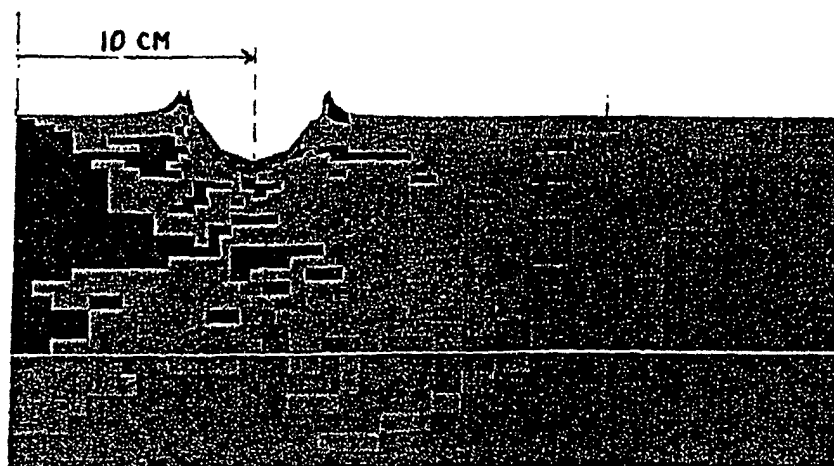


FIG. 11A

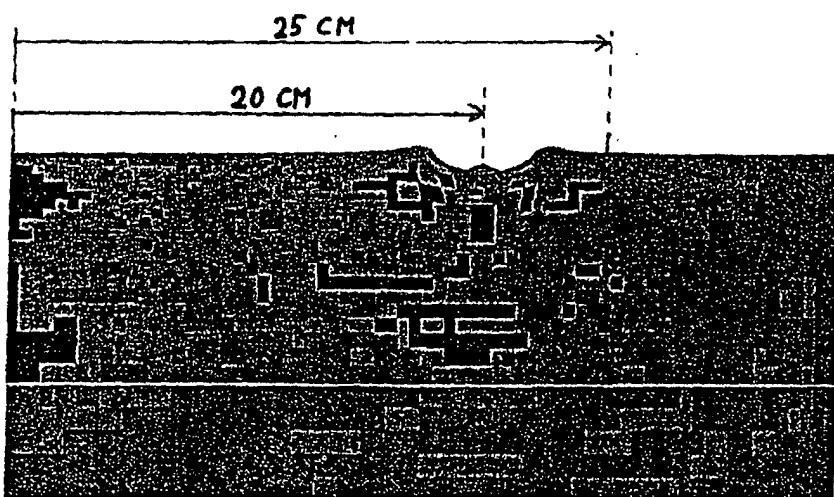
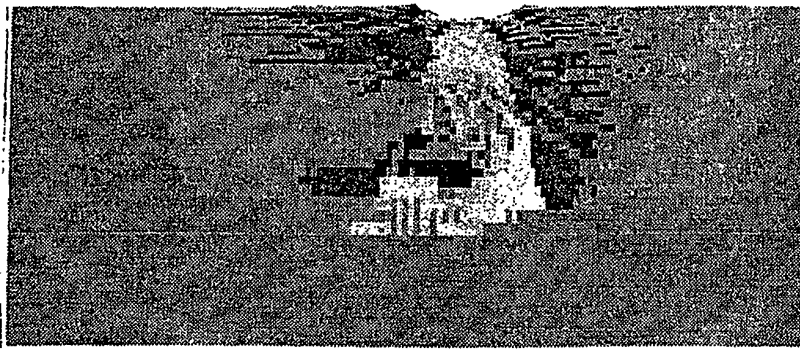


FIG. 11B

Toestand van het materiaal: elastisch, plastisch of bezwaken (donker), en een belasting op een straal van 20 cm en 10 cm.
Hierbij is het faalcriterium zwaarder (10 MPa) dan bij het uitgangsmodel (3MPa).



ELASTIC
 PLASTIC
 FAILED 11
 FAILED 22
 FAILED 33

FIG. 12A

CYCLE 350
 $T = 5.973E-02$

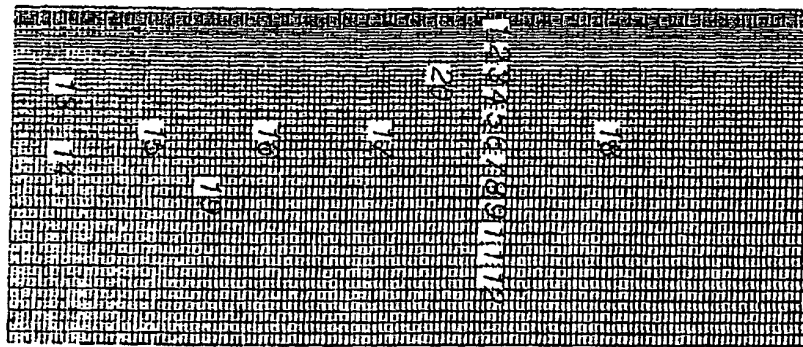
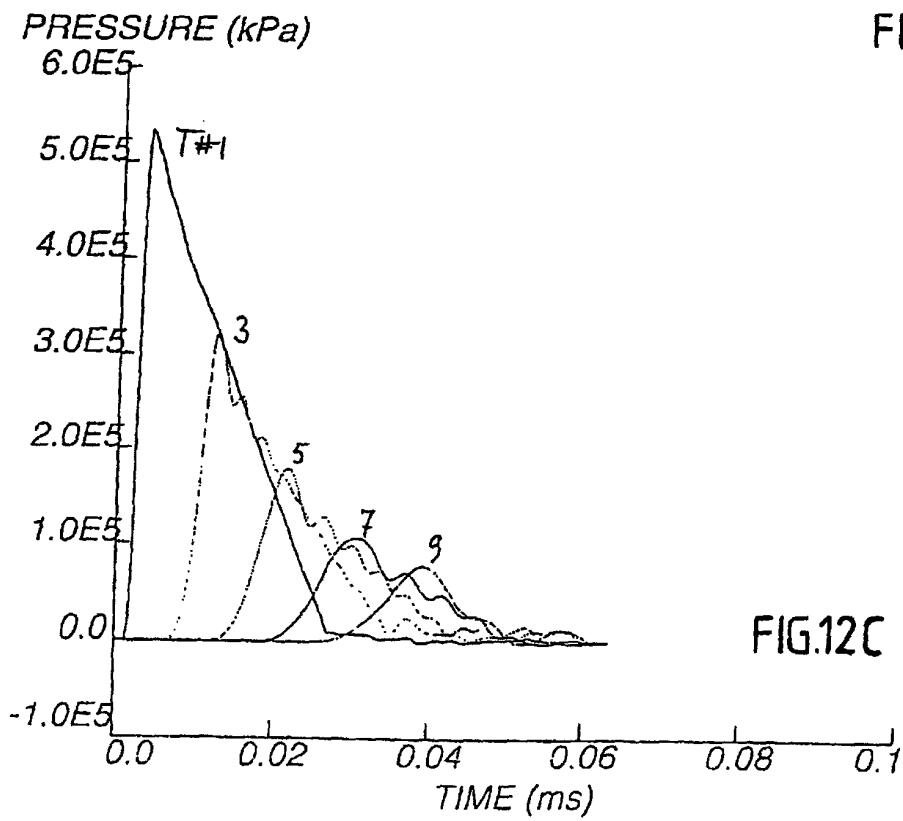


FIG. 12B



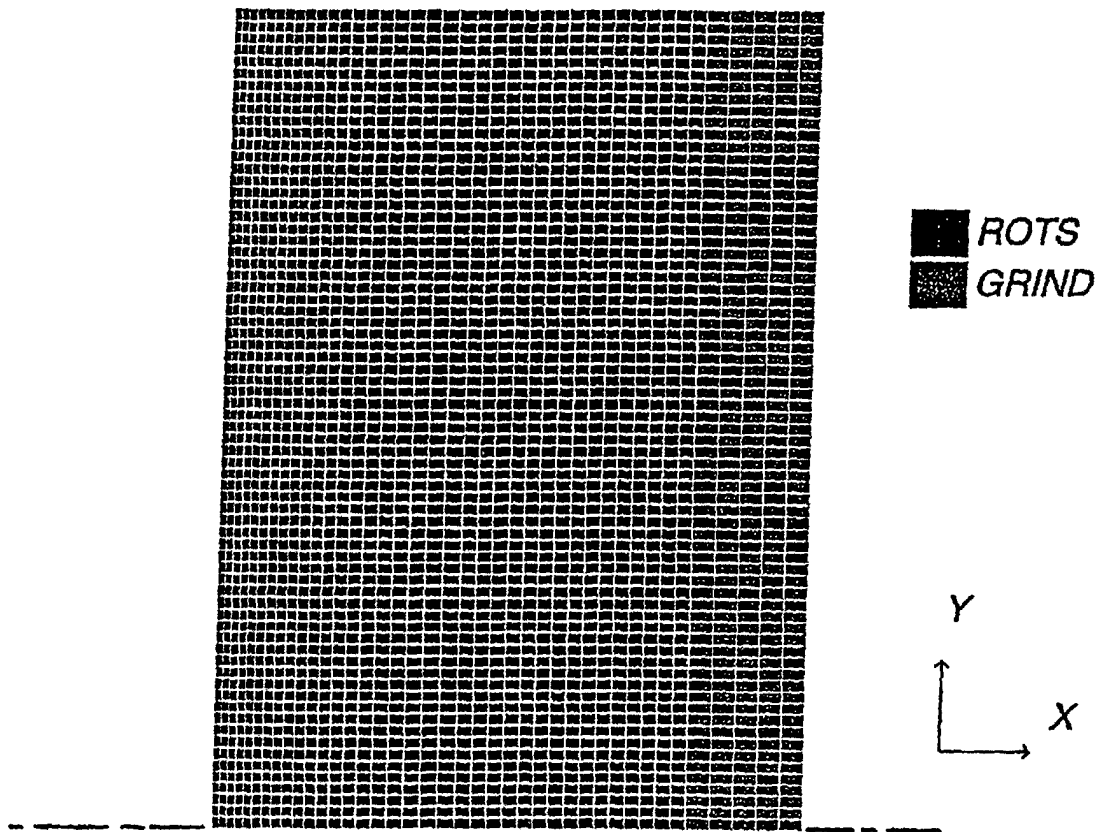
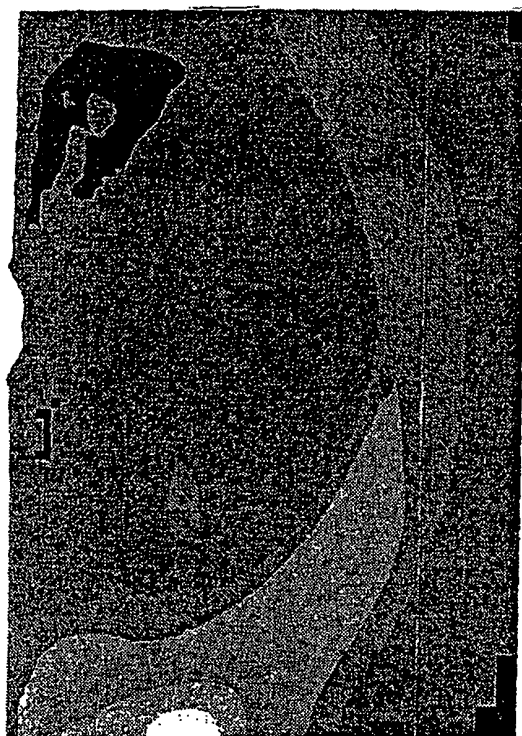


FIG.13A

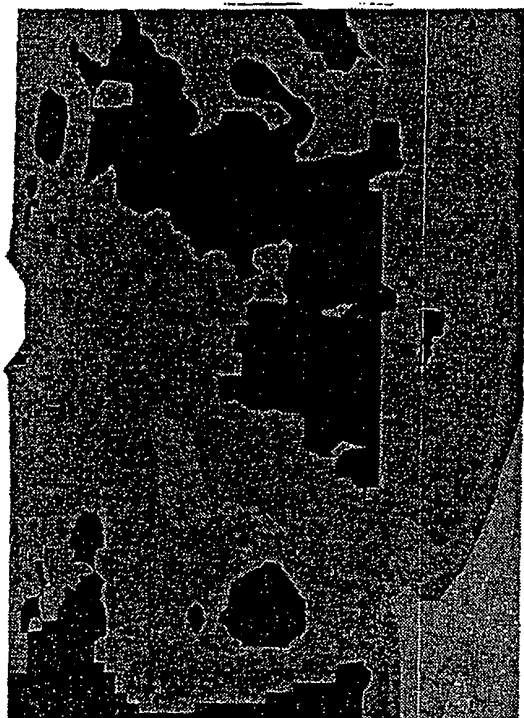
Grid en materiaalallocatie voor de simulatie, waarbij de dikte van de rotslaag 20 cm is.



CYCLE 150
 $T = 8.297E-02$ FIG.13B

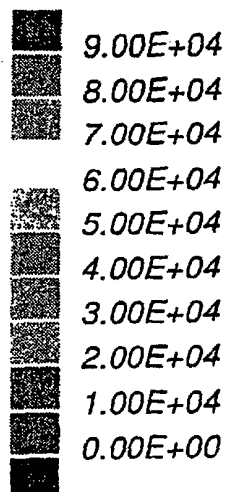


CYCLE 175
 $T = 9.502E-02$ FIG.13C

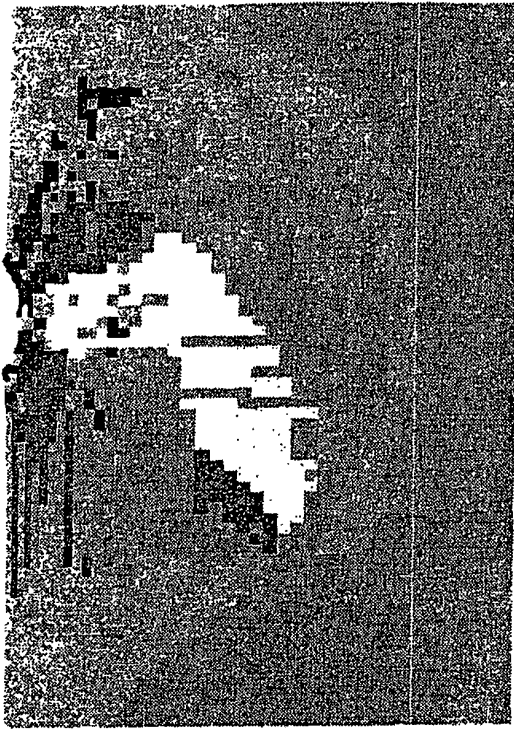


CYCLE 225
 $T = 1.181E-01$ FIG.13D

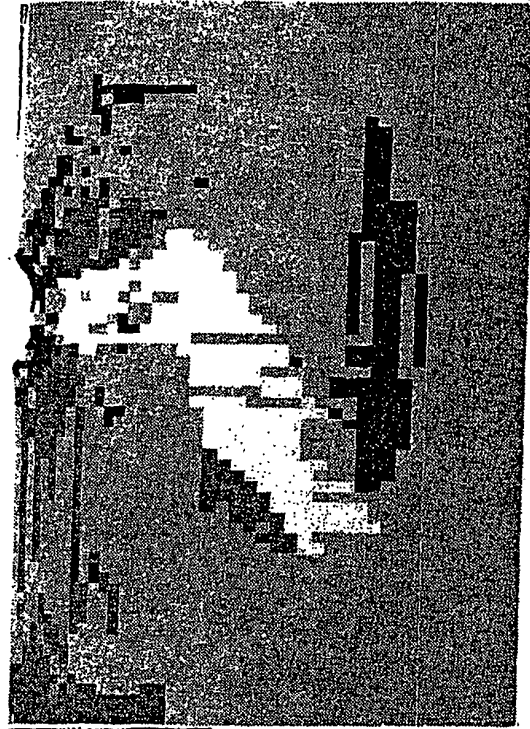
PRESSURE
 (kPa)



Drukverloop p in de rots en het grind op drie
 tijdstippen



CYCLE 150
 $T = 8.297E-02$ FIG.13E



CYCLE 175
 $T = 9.502E-02$ FIG.13F



CYCLE 225
 $T = 1.181E-01$ FIG.13G

-  ELASTIC
-  PLASTIC
-  FAILED 11
-  FAILED 22
-  FAILED 33

Toestand van het materiaal:
 elastisch, plastisch of bezwiken
 in 1,2 of 3 richting op drie tijd-
 stippen.

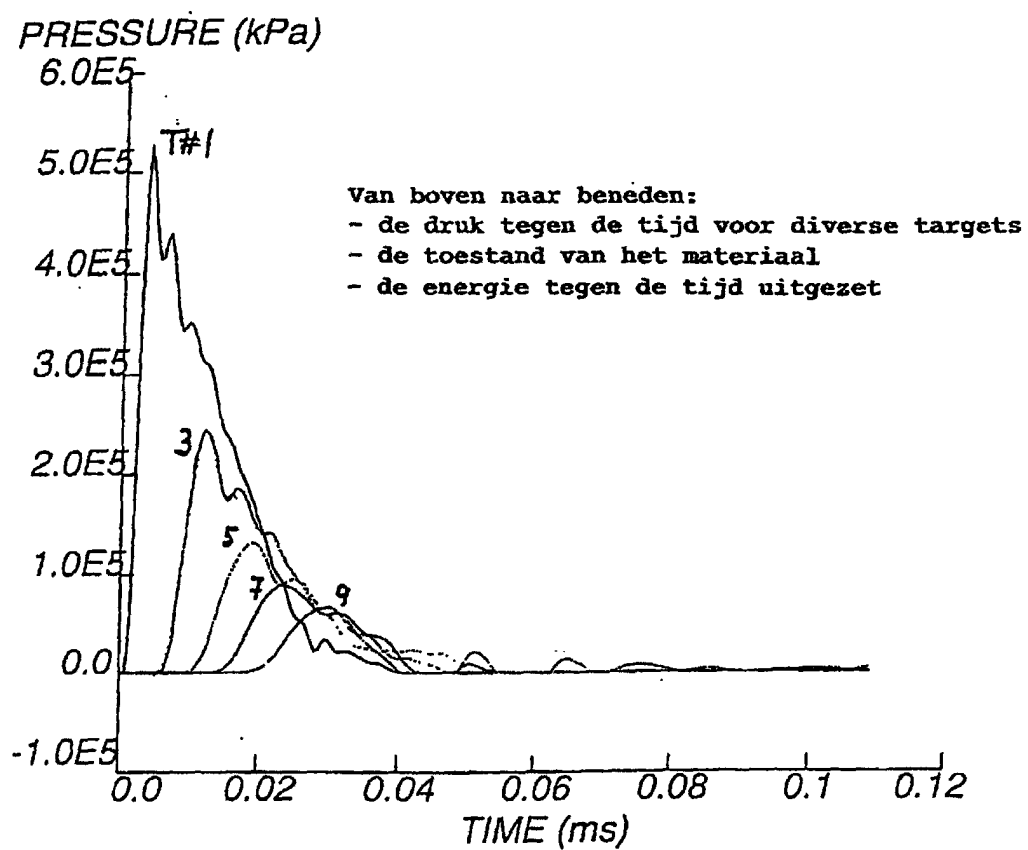


FIG.14A

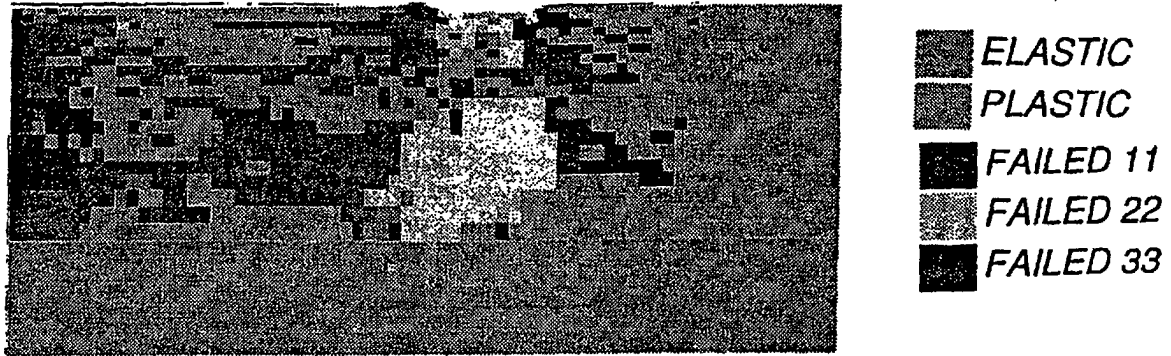


FIG.14B

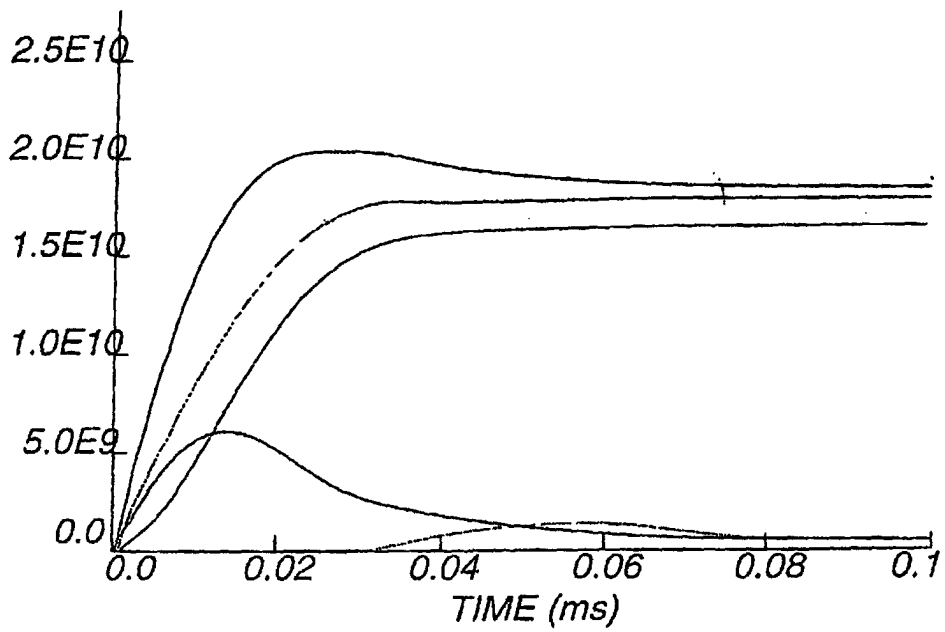


FIG.14C