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NUMERICAL SIMULATIONS OF GROUND SHOCK ATTENUATION LAYERS FOR SWEDISH RESCUE CENTRES AND SHELTERS

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Abstract

Light expanded clay shale aggregates ("LECA") is a very promising material for ground shock attenuation due to its low impedance. This has been verified both by shock impedance matching technique and by numerical simulations with AUTODYN™ [1].

To derive the mechanical properties of LECA, tri-axial compression tests with isotropic consolidation were performed on cylindrical specimens to obtain the porous equation of state ("EOS"). Additionally, tri-axial shear tests were performed at different pressure levels to obtain the pressure hardening yield surface.

Keywords: Ground Shock, Dry Sand, Saturated Clay, Light Expanded Clay Shale Aggregates, Mechanical Properties

1. Introduction

The Swedish Rescue Services Agency is the responsible authoritative for civil Rescue Centres and Shelters ("RC/S") in Sweden. Rescue Centres are built and planned for accommodation of the civil defence command during preparedness and war. These buildings are constructed as one- or two storey buildings, and often, one floor is below ground surface. The framework is made of reinforced concrete.

Rescue Centres and shelters are not made 'hit proof' for cost reasons. They are just designed to resist conventional weapon loads that detonate at a certain distance from the structure. Ground shock is one of the possible loads that is of interest. To protect the structure, its components, and the personnel of a RC/S against ground shock, a layer of a material with low impedance could be used. This type of added protection should be considered when the RC/S is surrounded by a dense and heavily saturated soil.

LECA have been recognised by many as a good attenuation layer [2] and a good material to irreversibly absorb energy. However, the following questions must be answered: How good is it in this application? How much will the maximum impulse and pressure decrease when a LECA layer in the front of the basement wall is utilised? What thickness should the LECA layer have for optimal impulse reduction? These questions will be treated in this paper.

2. Mechanical properties of LECA, Dry Sand, and Fully Saturated Clay

The Norwegian Geotechnical Institute ("NGI") have performed tri-axial tests on Light Expanded Clay Shale Aggregates 10-20 mm [3].

The mechanical properties of LECA were derived from four tri-axial cylindrical tests [3], and tri-axial shear tests up to 0.5 MPa [4]. The loading on the specimens were firstly isotropic consolidation ($P=\sigma_1=\sigma_2=\sigma_3$) with loading and unloading at different pressure levels. From these tests the porous Equation Of State ("EOS") and the mechanical unloading bulk modulus were derived. After the isotropic consolidation, shear tests at different pressure levels, i.e. 2, 4, 10, and 40 [MPa] were performed. The maximum pressure dependent yield surface was based on the data from these tests. The derived mechanical properties found for LECA are valid to pressure up to approximately 80 MPa. For higher pressures best fit lines were utilised to derive $P(\rho)$,$C(\rho)$, $\sigma_y(P)$, and $G(\rho)$. The *Granular material model*, implemented into AUTODYN^{TM} [1] was utilised for LECA and Dry Sand [5]. The utilised mechanical properties for LECA are shown in Table 1.

Table 1. Mechanical properties utilised for LECA with ρ_0=320.43 kg/m^3, and ρ_s=2500 kg/m^3

EOS, $P(\rho)$		Bulk sound speed, $C(\rho)$		Yield surface, $\sigma_y(P)$		Shear Modulus, $G(\rho)$	
ρ , [kg/m^3]	P, [MPa]	ρ , [kg/m^3]	C, [m/s]	P, [MPa]	σ_y(P), [MPa]	ρ , [kg/m^3]	G, [MPa]
320.43	0	322.60	351.7	0	0	322.60	27.40
368.98	0.952	330	823.9	20	26.247	330	153.82
726.08	4.847	400	893.1	40	52.495	400	219.09
1069.63	10.051	800	1288.6	60	78.742	800	912.17
1181.69	14.158	1200	1684.1	80	104.989	1200	2337.00
1300.00	22.659	1600	2079.6	100	131.237	1600	4751.36
1422.93	39.831	1950	2425.6	120	157.500	1950	7878.29
1700.00	145.960	2450	4000.0	200	157.500	2450	26917.89
2400.00	1801.771	2500	4057.1			2500	28257.00
2843.71	5657.290	2900	4057.1			2900	28257.00

The utilised mechanical properties for Dry Sand are shown in Table 2. In [5] the derivation of the mechanical properties for the sand is presented.

Table 2. Mechanical properties utilised for Dry Sand with ρ_0=1674 kg/m^3, and ρ_s=2641 kg/m^3

EOS, $P(\rho)$		Bulk sound speed, $C(\rho)$		Yield surface, $\sigma_y(P)$		Shear Modulus, $G(\rho)$	
ρ , [kg/m^3]	P, [MPa]	ρ , [kg/m^3]	C, [m/s]	P, [MPa]	σ_y(P), [MPa]	ρ , [kg/m^3]	G, [MPa]
1674.0	0	1674.0	265.2	0	0	1674.0	76.9
1739.5	4.577	1745.6	852.1	3.401	4.235	1745.6	869.4
1873.8	14.980	2086.3	1721.7	34.898	44.695	2086.3	4031.7
1997.0	29.151	2146.8	1875.5	101.324	124.035	2146.8	4906.9
2143.8	59.175	2300.0	2264.8	184.650	226.000	2300.0	7769.0
2250.0	98.098	2572.0	2956.1	500.000	226.000	2572.0	14800.9
2380.0	179.443	2598.0	3112.2			2598.0	16571
2485.0	289.443	2635.0	4600.0			2635.0	36718
2585.0	450.198	2641.0	4634.0			2641.0	37347
2671.3	650.660	2800.0	4634.0			2800.0	37347

Fully saturated clay with initial density of 1908 kg/m^3 was modelled with *Shock* EOS [1]. A linear relationship between shock velocity ("U_s") and particle velocity ("U_p") was defined with C_1=1497 m/s and S_1=1.876. Shock Hugoniot Data [6] for water and water saturated *Tuff* were used to establish the U_s-U_p relationship. The *Von Mises* yield surface was defined as a strength model with the yield strength 0.5 MPa, and the shear modulus 1973.5 MPa.

A *Hydro Tensile Failure Limit* [1] with a small negative pressure value was defined for all materials. The reheal option was utilised.

3. Shock Attenuation Layer for Added Protection for the RC/S Against Ground Shock Loads

When a shock wave with pressure, P_1, and Particle velocity, U_{p1}, is transmitted from the soil into a material with lower impedance, e.g. LECA, the pressure, P_2, will decrease and the particle velocity, U_{p2} will increase. This can be easily illustrated by a graphical solution, shown in Chapter 3.2. But the real ground shock problem is much more complicated. Firstly the energy release from the detonation of high explosive charge have to be accounted for, then the attenuation of the pressure wave in loose soils is approximately proportional to the (radius)^3. The soil ability to transmit the pressure wave is highly proportional to the amount of water in the soil, i.e. how much of the air voids in the soil is filled with water. Then the stress wave propagation from a detonated HE charge near the surface is not easy to interpret, especially when an attenuation layer with lower impedance is utilised in front of the basement wall. In Figure 1 the stress waves are schematically illustrated. The *Direct wave* will be the first to arrive at the *Observation point* from the *Explosive source*. With a buried charge a *Relief wave* will be generated when the ground shock wave reaches the air, which has, very low impedance compared with the soil. A possible third wave is a *Reflected wave* that can be generated when the propagating wave is reflected against a deeper soil layer with higher impedance. All these waves build up the observed *Resultant wave.*

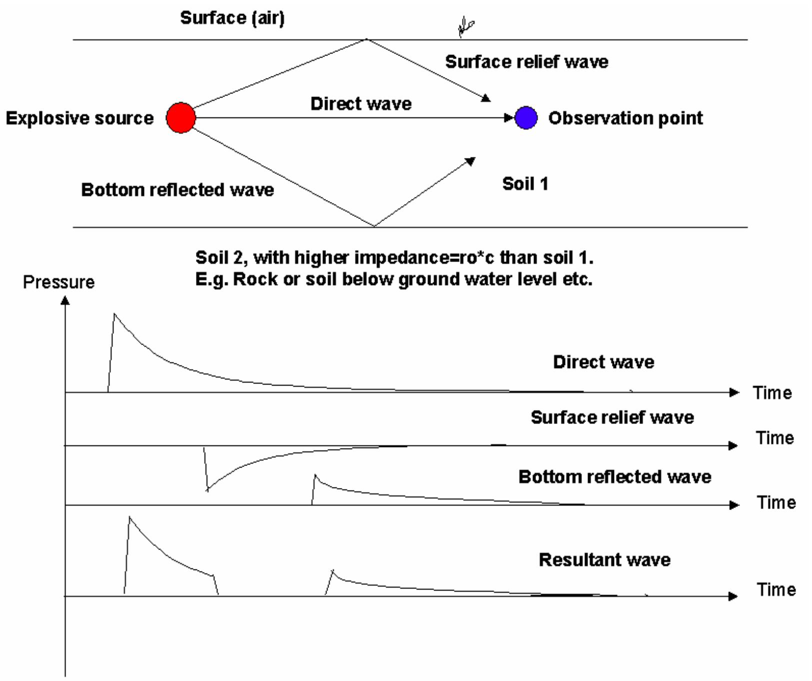

Figure 1. Schematic illustration of how the *Resultant wave* is generated when a fully buried HE charge near the surface is detonated.

When a layer with lower impedance is introduced in front of the basement floor the stress waves get even more complicated, as indicated in Figure 2. In this case when the *Direct wave* reaches the layer with lower impedance a *Relief wave in the sand* is generated. This relief wave disturbs the pressure build up for the continuing process in the sand. This is a very positive effect that decreases the total load of the ground shock. The transmitted wave now reflects between the concrete wall and the soil, this effect is not desired, because the maximum impulse will increase. However, this is not a major issue for LECA; the attenuation and energy absorption of shock waves is very good, but it is important that the layer is designed with sufficient thickness and drainage to ensure a dry attenuation layer of LECA with low density 250 – 350 kg/m^3.

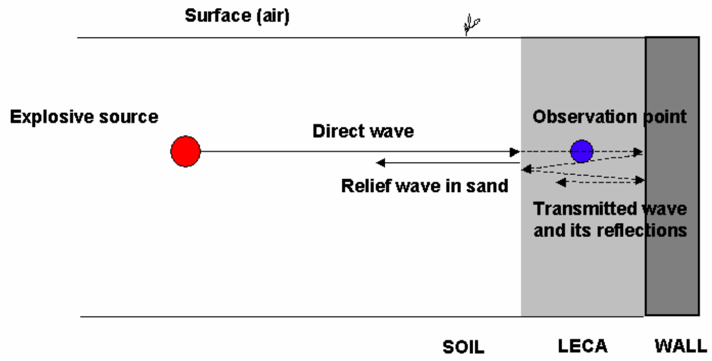

Figure 2. Schematic illustration of how the *Direct wave* generates a *Relief wave in sand* when it reaches the low impedance layer, and how the transmitted wave in the LECA bounces between the concrete wall and soil, both with higher impedance.

The LECA layer will also have a positive effect when the crater is generated since the layer deforms easily upwards and therefore will generate lower dead mass load on the structure. With the hydro code AUTODYN™ all these effects can be accounted for, as done in Chapter 3.3.

3.1 Graphical Solution by Shock Impedance Matching Technique

A Graphical solution for the transmission of a shock wave from a material with high impedance (e.g. soil) to a material with low impedance (e.g. LECA) can easily be done by a so called shock impedance matching technique. This is thoroughly explained in [7].

To study the transmitted shock wave the conservation laws of mass, momentum and energy are needed:

$$\rho_0 \cdot U_s = \rho \cdot (U_s - U_p)\,, \tag{1}$$

$$P - P_0 = \rho_0 \cdot U_s \cdot U_p\,, \text{ and} \tag{2}$$

$$E - E_0 = \tfrac{1}{2} \cdot (P + P_0) \cdot (V_0 - V)\,. \tag{3}$$

Equations (1)-(3) have five variables, pressure (P), particle velocity (U_p), shock velocity (U_s), specific volume ($V=1/\rho$), and energy (E). Consequently one additional equation (EOS) is necessary to close the equation system.

By using equation (1) and (2), the shock wave velocity, U_s, and particle velocity, U_p, can be described as functions of pressure, P, and specific volume, V, i.e.

$$U_s^2 \cdot \rho_0^2 = \frac{P - P_0}{V_0 - V} \quad \text{or} \quad U_s = V_0 \sqrt{\frac{P}{V_0 - V}} \text{ when } P_0 = 0, \text{ and} \tag{4a,b}$$

$$U_p^2 = (P - P_0) \cdot (V_0 - V) \quad \text{or} \quad U_p = \sqrt{P \cdot (V_0 - V)} \text{ when } P_0 = 0. \tag{5a,b}$$

In this case the plastic compaction curve from the EOS will be utilised for the Dry Sand and LECA, see Table 1 and Table 2. The piecewise linear curves describe the pressure as a function of density and will be equivalent to the Hugoniot line.

The utilised EOS for saturated clay is described as a linear function between shock wave velocity and particle velocity, i.e.:

$$U_s = C_1 + S_1 \cdot U_p\,. \tag{6}$$

By inserting (6) into (2) the pressure can be calculated as a function of particle velocity:

$$P = \rho_0 \cdot (C_1 + S_1 \cdot U_p) \cdot U_p \text{ when } P_0 = 0. \tag{7}$$

The density can be calculated as function of particle velocity when (6) is inserted into (1):

$$\rho = \frac{\rho_0 \cdot (C_1 + S_1 \cdot U_p)}{(C_1 + S_1 \cdot U_p) - U_p}\,. \tag{8}$$

Now the relationships for pressure as a function of density, shock wave velocity as a function of particle velocity, and finally the pressure as a function of particle velocity can be plotted for Dry Sand, LECA, and Saturated Clay, seen in Figure 3 and Figure 4.

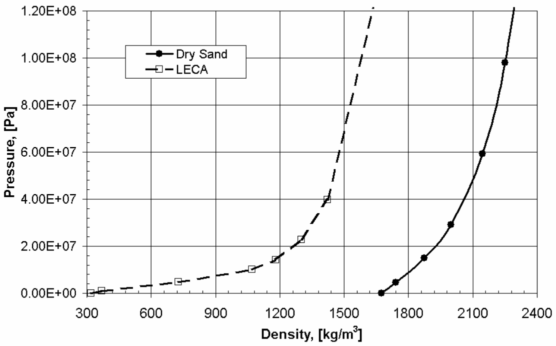

Figure 3a. Pressure as a function of density for Dry Sand and LECA.

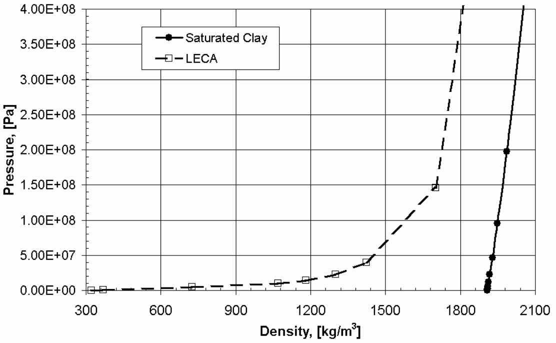

Figure 4a. Pressure as a function of density for Saturated Clay and LECA.

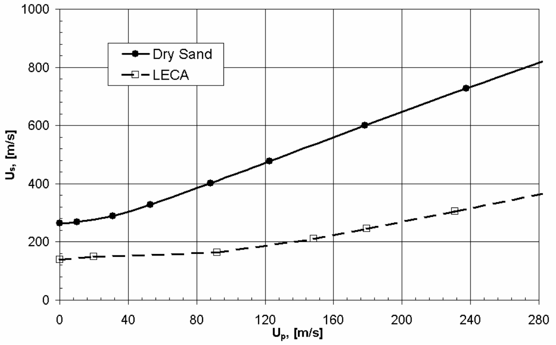

Figure 3b. Shock wave velocity as a function of particle velocity for Dry Sand and LECA.

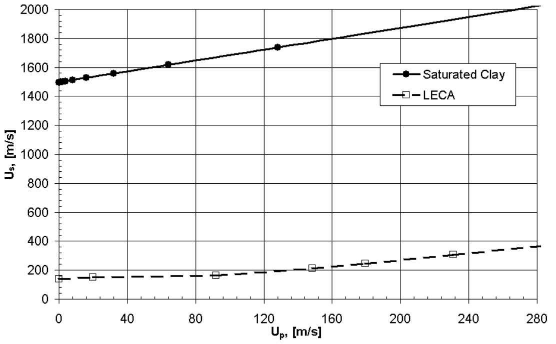

Figure 4b. Shock wave velocity as a function of particle velocity for Saturated Clay and LECA.

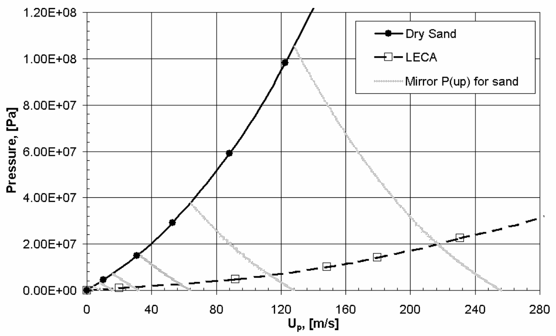

Figure 3c. Pressure as a function of particle velocity for Dry Sand and LECA.

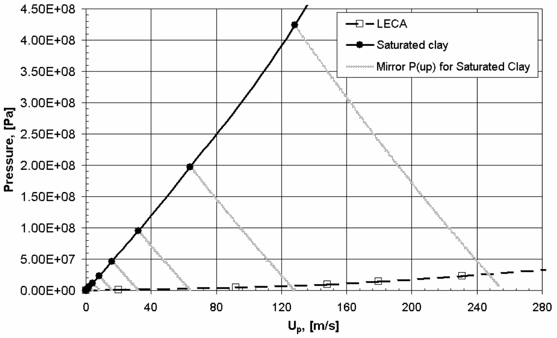

Figure 4c. Pressure as a function of particle velocity for Saturated Clay and LECA.

Now the P-U_p curves can be used to predict the maximum pressure and particle velocity of the transmitted shock wave. This is done by assuming a (P, U_p) pair for the soil and then make a mirror of the P-U_p curve for the soil and the intersection point with the LECA curve gives the actual pressure and particle velocity in LECA. This have been done for particle velocities U_p = 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64, and 128 m/s for both Dry Sand and Saturated Clay, see Figure 3c and 4c. The results are also shown in Table 3 and 4.

According to the graphical solution the maximum pressure decreases in average 80 percent when the shock wave is transmitted from Dry Sand to LECA for particle velocities of 0.25 m/s to 128 m/s. For Saturated Clay the average decrease is estimated to be 96 percent! The decreases are very important because this will directly lead to lower impulses. But how thick should the attenuation layer be for optimal decrease in impulse? This will be discussed in Chapter 3.2

Table 3. Graphical solution for transmitted shock wave from Dry Sand to LECA.

$U_{p,\ sand}$ [m/s]	P_{sand} [MPa]	$U_{p,\ LECA}$ [m/s]	P_{LECA} [MPa]	Decr. P, [%]	Incr. U_p, [%]
0.25	0.10	0.45	0.02	79.22	79.20
0.50	0.21	0.90	0.04	79.23	79.20
1.00	0.42	1.79	0.09	79.47	79.40
2.00	0.84	3.59	0.17	79.43	79.30
4.00	1.69	7.17	0.35	79.57	79.30
8.00	3.44	14.35	0.69	79.92	79.35
16.00	7.16	26.61	1.43	80.07	66.34
32.00	15.61	57.07	2.97	81.00	78.34
64.00	37.61	113.24	6.56	82.55	76.93
128.00	105.03	216.75	19.96	80.99	69.34

Table 4. Graphical solution for transmitted shock wave from Saturated Clay to LECA.

$U_{p,\ Clay}$ [m/s]	P_{Clay} [MPa]	$U_{p,\ LECA}$ [m/s]	P_{LECA} [MPa]	Decr. P, [%]	Incr. U_p, [%]
0.25	0.71	0.49	0.03	96.40	96.40
0.50	1.43	0.98	0.05	96.60	96.60
1.00	2.86	1.97	0.09	96.70	96.70
2.00	5.73	3.93	0.19	96.71	96.70
4.00	11.48	7.87	0.38	96.72	96.70
8.00	23.08	15.73	0.76	96.71	96.68
16.00	46.62	31.45	1.57	96.63	96.56
32.00	95.07	62.85	3.29	96.54	96.41
64.00	197.50	125.32	7.68	96.11	95.81
128.00	424.20	247.20	25.41	94.01	93.13

3.2 Numerical Simulations with AUTODYN™

Numerical simulations are useful when the whole ground shock phenomena is accounted for. The purpose with the simulations was to find an optimal thickness of the shock attenuation layer when the decrease in maximum impulse and pressure were considered.

The studied High Explosive charge was a fully buried cylindrical TNT charge with height 1.1 m and radius 0.149 m, and the centre of gravity at 1.5 m below ground surface. The charge weight was 125 kg TNT. The *Jones Wilkins Lee* EOS [1] was utilised to simulate the energy release from the detonation, and the stand off distance to RC/S was set to 5 metres.

To account for the large mass transport, the multi material *EULER processor* [1] was utilised to solve the basic continuum differential equations. A two-dimensional axi-symmetrical model with a rectilinear mesh and a cell size of 25 mm was utilised in the area 4 m times 5 metres, outside the mesh was gradually coarsened. The air was modelled as void cells, the RC/S was modelled as a fully reflected wall, an *outflow boundary* [1] was defined in the top in the air, and finally a *transmit boundary* [1] was defined at the bottom in the soil. In Figure 5 the material locations and boundaries are shown.

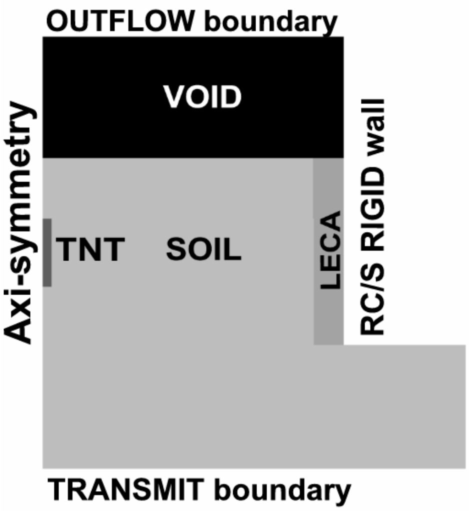

Figure 5. Material locations and boundaries of the 2D axi-symmetrical model. The stand off distance from the charge to the wall is 5 m, the charge centre of gravity was set to 1.5 [m] below ground surface.

LECA layers with thickness: 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0 were studied together with both soil types: Saturated Clay and Dry Sand. The results from one target point in front of the rigid wall was studied, with a depth of burial 1.5 m and a stand off distance to target 5 m. The decrease in reflected maximum pressure and maximum impulse at the rigid wall are shown in Figure 6 and Figure 7.

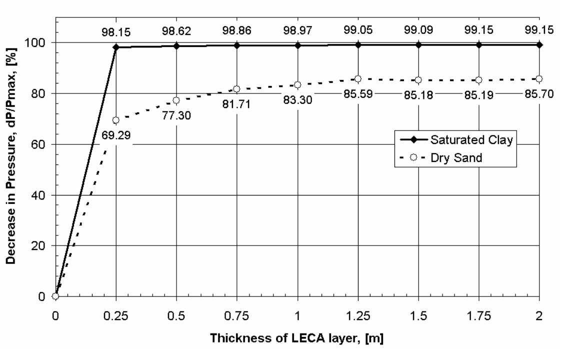

Figure 6. Decrease in maximum pressure when different thickness of LECA layer is used.

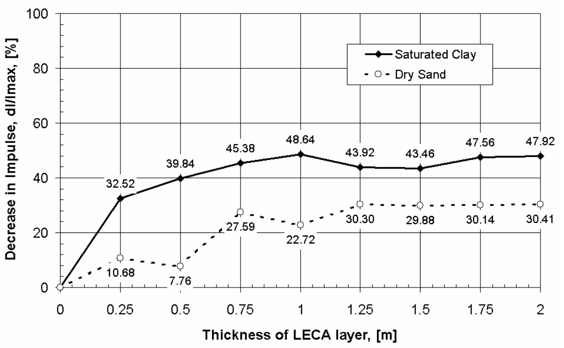

Figure 7. Decrease in maximum impulse when different thickness of LECA layer is used.

Figure 6 shows significant reduction of the maximum reflected pressure even for thin LECA layers for both soil types, but the main focus should be on the reduction of the impulse. This would need a certain thickness for optimal reduction. Figure 7 shows that the thickness of the attenuation layer should be at least 1 m to achieve 45 percent reduction in maximum impulse when Saturated Clay is considered. For Dry Sand it should be at least 1.25 m to achieve 30 percent reduction in maximum impulse.

Figure 8 shows the shock wave in Dry Sand when it has propagated to the LECA layer. Notice the relief waves generated both from surface and from the LECA layer.

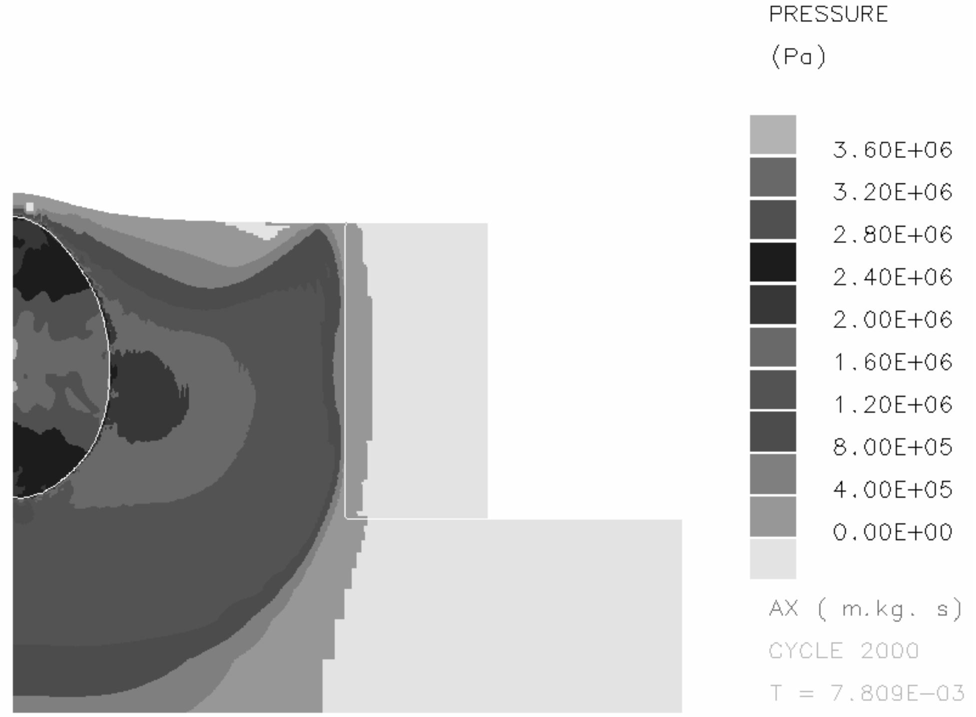

Figure 8. Pressure plot of the shock wave propagation in Dry Sand at 7.8 ms. Thickness of LECA layer was 1.5 m

In Figure 9 the crater size is shown at 97 milliseconds for the Dry Sand simulation with a LECA layer thickness of 1.5 m. The crater depth and radius were 3.5 m and 2.9 m respectively. Notice also the deformed LECA layer.

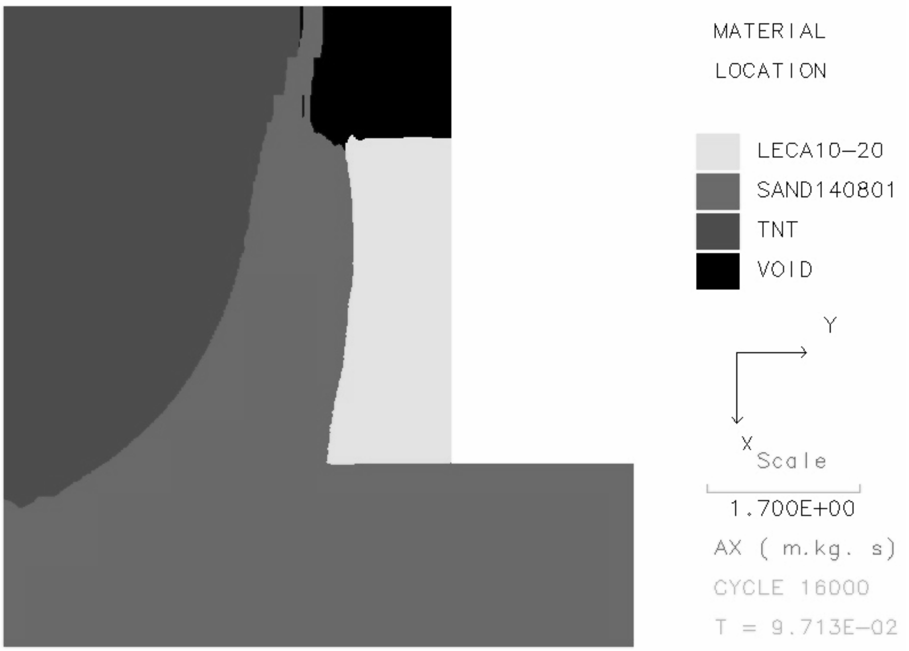

Figure 9. Material location for Dry Sand at 97 ms. The thickness of the LECA layer was 1.5 m.

4. What if the charge detonates inside the LECA layer?

If the charge detonates inside the LECA layer will this be worse than the normal soil backfill material? This part has not been studied here, but small scale cylindrical confinement experiments with the purpose to study different materials and their ability to absorb the energy from a detonation concluded that LECA absorbs more energy than e.g. sand [8].

5. Conclusions

The graphical solutions and numerical simulations show that LECA is a good attenuation layer to reduce the maximum pressure and maximum impulse; most useful it seems to be for Saturated Clay.

The thickness of the attenuation layer should be at least 1 m when the RC/S is surrounded with Heavily Saturated Clay to achieve approximately 45 percent decrease in impulse for the studied load case. A thickness above 1.25 m of the attenuation layer should be used for optimal decrease in impulse when Dry Sand is considered. The different thickness for the two soil types is certainly related to the actual wavelength of the shock wave, this will be further studied.

6. References

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