Analysis of an Underground Gallery Under Aircraft Impact

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1 Generalities

The stresses and vibrations in an underground gallery, under the impact of an aircraft, depend of the thickesses and of the characteristics of the earth cover and of the behaviour of an eventual protective slab at the ground surface.

If the gallery is not deeply embedded, the earth cover and the roof of the gallery behaves locally non linearly, in particular when the deformations of the broken protective slab are very large in the zone of impact.

At the ends of the gallery, the presence of neighboring buildings can strongly affect the amplitudes of the stresses and accelerations, due to the rebound of the pressure waves combined with the weakened end zones of the protective slab and of the roof of the gallery.

This paper describes the methods used to calculate the response spectra of acceleration and the stresses in the gallery taking into account the non linear behaviour of concrete and of the backfill in the region of impact. The local effects of penetration and crushing of concrete were approximated, because the consideration of those effects would have necessitated a too detailed model of the projectile and the target.

2. Description of the gallery and the soil conditions.

The analyzed gallery has a rectangular section with a length of 40 m and connects two heavy buildings.Its transversal dimensions are given on fig. 1. The gallery rests on alternate horizontal layers of rock (G av = 1000 Mpa) and alterated shale (G av. = 500 Mpa). The tunnel is covered by 2 meters of backfill (G est = 100 Mpa) and protected by a 90 cm thick protective slab made of reinforced concrete.

3. Load and impact conditions.

The aircraft is supposed to crash vertically on the slab, with a crash area of 7 m^2. Its load function has a duration of 70 ms and a peak value of 110 MN (see Fig. 2 and Ref. 1).

The impact is supposed to occur at four locations on the crash slab : - the center of the tunnel; - at the end of the tunnel, on the longitudinal symmetry axis; - at the center on the edge of the slab, - at 4,5m from the end of the tunnel, on the edge of the slab.

One additional load case was considered : - a centered impact with a linear behaviour of the concrete of the protective slab.

4. Analysis of the gallery.

4.1 Method of analysis

Large plastic deformations were expected in the vicinity of impact, so it was decided to perform a non liner F.E. dynamic analysis, using an explicit algorithm with a Lagrangian system of reference (Ref 2).

4.2 Soil and concrete parameters

Backfill : From oedometric and triaxial tests showing no cohesion for the type of backfill used, one has selected a Drucker-Prager combined with a Von Mises rupture surface with a third order polynomial behaviour law in loading and a first order polynomial law in unloading (fig. 3). Since no triaxial tests were available at high pressures - more than 40 bars - the Von Mises rupture limit ($\sqrt{J_2}$) was supposed higher than 50 bars.

Soil of foundation : The layers of rock and alterated shale are supposed to behave linearly.

Concrete of the protective slab : In the zone of impact one can assume that the concrete is cracked, at least in bending, because the thickness of the slab is not large enough to avoid rupture. A Drucker-Prager rupture law was selected, with elastic properties taken as the half of the common properties of a B25 concrete (see Fig. 4)

Concrete of the gallery : This concrete will follow the same law as the one used for the slab, but with the full concrete elastic characteristics.

4.3 Model of the gallery and the soil, boundary conditions.

8 nodes Lagrangian bricks elements, with one integration point and antihourglass viscosity have been used to model the soil and the gallery. The slab and the concrete walls are represented by at least 3 layers of elements (see Fig. 5). The backfill is modelled with bricks elements having edge length of about 30 cm in the vicinity of impact, to have a correct propagation of waves at least for 40 Hz.

The boundaries were placed at a sufficient distance from the gallery (about 200 m) to avoid interferences in the zone of interest between the incident and the reflected waves during the 150 ms of the simulation calculations.

The dimensions of the elements are increased from the location of impact to the edges of the model as represented on figure 6 showing one of the 40 common cross sections of the larger 3D model.

The total amount of elements was of about 16000 for the smallest symmetrical model and of about 64000 for the largest 3D model.

5. Result of analysis

The self-adjusting time step is of about 0,025 ms, giving approximately 6000 steps made in 3 to 7 restarts on a CRAY 2.4 computer using the vectorized RADIOSS computer code (Ref. 2)

5.1 Stresses and deformations distributions.

The protective slab withstand large vertical deformations in the zone of impact (max. deflection of 0.41 m). The backfill behaves nonlinearly as well as the roof of the gallery (max. deflection 0,0135 m). For the case of an impact at one end of the gallery, those deflections are more than twice those of the case of the centered impact.

The pressure and the Von Mises stresses in the backfill under impact does not expand as much laterally as could be expected but seems to concentrate in a cylinder centered on the impact axis; this is probably due to the large local deflections of the protective slab. This is confirmed by an analysis made for an elastic protective slab which showed a larger diffusion of the pressures waves and then smaller deflections of the roof of the gallery (see Fig. 7).

The gallery itself behaves as a beam on continuous springs. In the case of the impacts on the edge of the protective slab, the vertical pressures on the roof are reduced but the horizontal pressure waves have created a significant torsion of the gallery around its longitudinal axis.

5.2 Accelerations.

The largest vertical accelerations (see table 1) in the gallery are obtained in the roof zone under impact and in particular for the impact at one end on the longitudinal axis. They are reduced by about the half for the impact on the edge of the slab, but the observed horizontal accelerations are then of the same magnitude than the vertical accelerations.

The effect of the non linearities under impact in the roof of the gallery can be observed at about 40 Hz in the response spectra (fig. 8), for the impact on the longitudinal axis (centered or at one end). The actual first frequency of vibrations of the roof is decreased by the nonlinearities, causing a pseudo tuning effect between the plate amplifications and the peaks of the spectral content of the applied impact force. This effect is not observed in the case of the linear protective slab.

At a certain distance from the impact (+/- 9 m), the relative differences between the amplitudes of accelerations are smaller, due to the attenuation of the direct compression waves and of the roof vibrations. The results of the different impact locations have similar amplitudes, except for the rocking effects; the vibrations at those points are similar to those obtained with a linear analysis of a beam shaped embedded structure.

6. Conclusions

Even if there are unknowns and uncertainties in the characteristics of the materials (concrete of the slab, backfill behaviour under high dynamic stresses), this analysis shows that the local effects influence strongly the forces and vibrations in the gallery, what cannot be seen with linear calculations for which the frequency content of the model is often limitated to 15 or 20 Hz; moreover, the nonlinear analysis shows also that the linear results might be underestimated in the vicinity of impact.

A correct definition of the behaviour of the backfill under high stresses is necessary and tests have to be made to obtain the parameters needed to create the adequate rupture and behaviour laws. It seems appropriate to use 2D explicit nonlinear analysis (plane or axisymmetric models) to design the dimensions of the protective slab, the thickness of the backfill and to determine the level of stresses for which the backfill must be tested. Such approach will probably help to reduce the local effects, allowing afterwards the use of simpler linear methods to determine the envelopes of stresses and accelerations in the gallery.

To reduce the amplitudes of the vibrations and of the stresses for an impact at the end of the gallery, it might better to limit the deflection of the protective slab by increasing locally its thickness or by supporting this plate on the adjacent buildings which must also, very often, withstand the aircraft impact.

7. References

[1] Richtlinien für die Bemessung von Stahlbeton von Kerkraftwerken für außergewöhnlicheäußere Belastungen , GBFT Mitteilungen 6/74.

[2] RADIOSS - a F.E. explicit computer program for crash and nonlinear dynamic impact problems- MECALOG - PARIS - FRANCE

	Section under impact			Section at 9 m from impact		
	Long.	Transv.	Vertic.	Long.	Transv.	Vertic.
Centered	0.	0.	225.	11.	0.	27.
End on axis	227.	0.	1137.	36.	0.	27.
Center Edge	0.	146.	217.	10.	31.	14.
4,5m End Edge	46.	40.	145.	19.	29.	23.
Center. el.	0.	0.	144.	27.	0.	41.

Table 1. Averaged maximum accelerations [m/s^2]

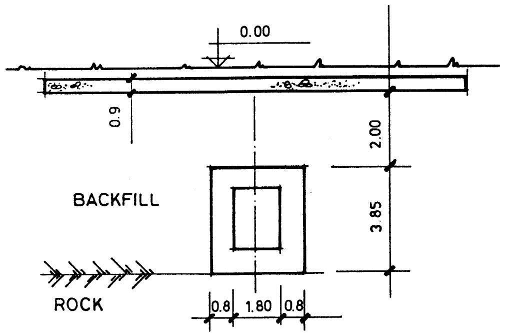

FIG. 1 CROSS SECTION

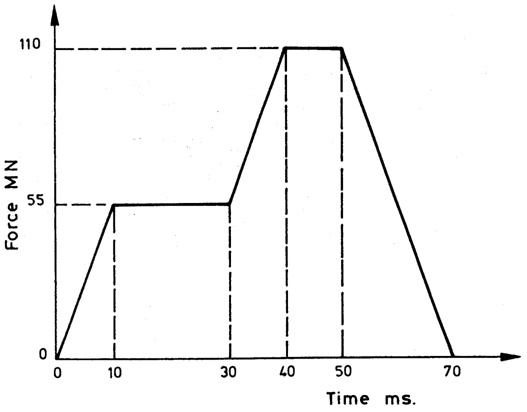

FIG. 2 AIRCRAFT IMPACT LOADING FUNCTION

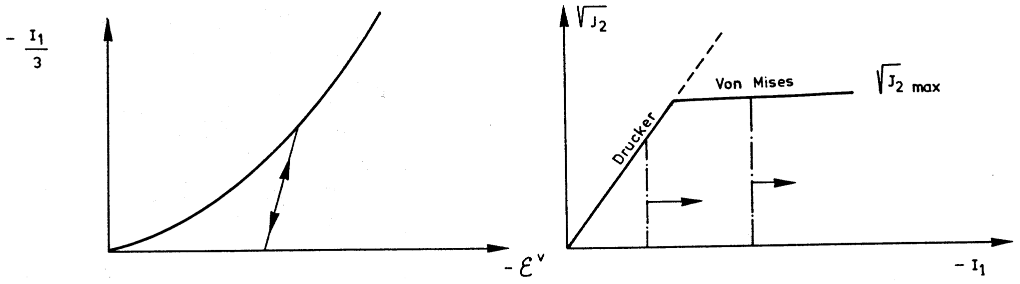

FIG. 3 BACKFILL : Rupture and plasticity laws

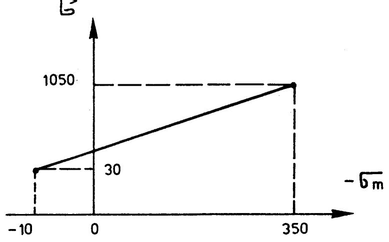

FIG. 4 Concrete plasticity criterion

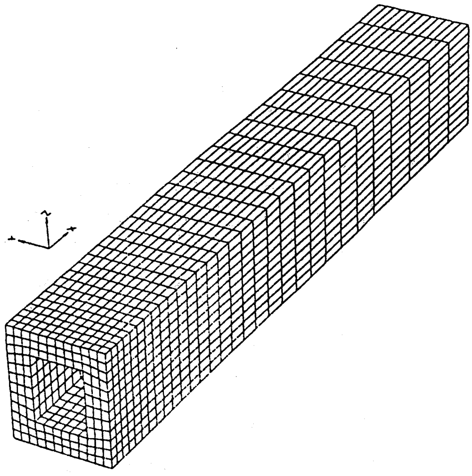

FIG.5 F.E. Model of the gallery

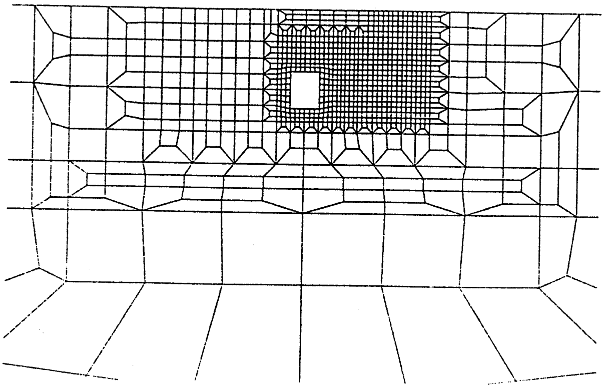

FIG. 6 F.E. Model in the vicinity of impact

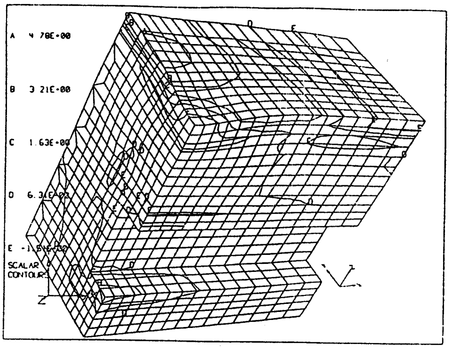

FIG. 7 Pressure distribution under impact

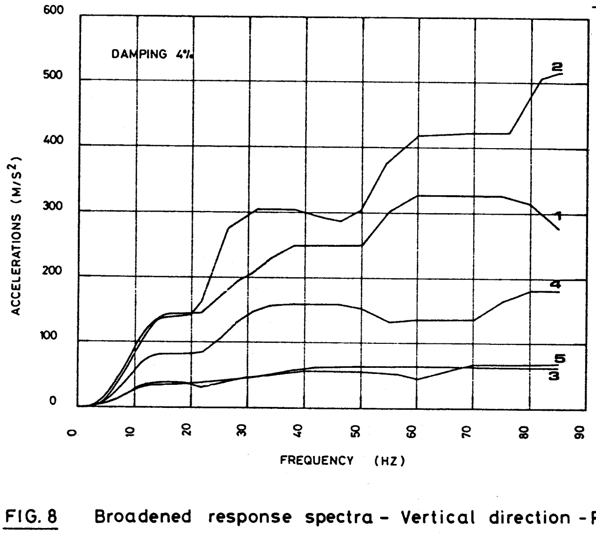

FIG. 8 Broadened response spectra - Vertical direction - Roof of the gallery

1 Impact at the center, on axis, non linear analysis
2 Impact at the end, on axis, non linear analysis
3 Impact on the edge, non linear analysis
4 Impact at the center, on axis, linear analysis
5 Impact at the end, on axis, non linear analysis

Curves 1 to 4 are given for the section of impact.
Curve 5 is obtained at 9m of impact.