# HELICOPTER CRASHWORTHINESS ON SOFT SOIL: CRASH CASES STUDY, STRUCTURE ELEMENTS TESTS AND NUMERICAL SIMULATIONS

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# *ABSTRACT*

*A first Research & Technology program on helicopter crashworthiness underlined through a crash cases study that nearly half of helicopter accidents occurs on soft soils, that is to say earth, sand, snow and water. Therefore, a second program was launched by DGA*[1] *to study helicopter crashworthiness on soft soil, involving industry, laboratories and official services.*

*This paper aims at presenting three different phases of this program that all show, at the end, a comparison between standards used to design helicopters and the crashworthiness of as-built rotorcrafts on soft soil.*

*The first phase is a study of real crash cases on soft soils. Accidents of civil and military helicopters were studied so as to find the rotorcrafts speed and attitude at the impact in survivable and non-survivable cases. Then these data are compared to the crash survivability envelope defined in MIL-STD*[2]*, to check their convenience towards soft soil crashes.*

*The second part presents the drop tests performed at DGA TA*[3] *(former CEAT*[4]*) to evaluate both soil and structure. Indeed, rigid specimens were dropped so as to get data on soil dynamic behaviour (earth, sand and water were used). Then, structural elements were tested to check their behaviour when impacting soft soil, which is particularly important for absorbers.*

*The third and last part deals with the evaluation of the explicit FEM*[5] *code RADIOSS to model soft soils behaviour and their interaction with the dropped specimens (rigid and flexible). Different methodologies are implemented and finally evaluated by comparison with the tests performed at DGA TA*[3]*. Numerical simulation results are confronted to experimental data in terms of deceleration profile and maximum soil penetration.*

*Different methodologies were evaluated: in a first step, a macro-modelling method is investigated, in which the interaction with the soil is modelled by non linear calibrated springs whose properties are identified from experimental load-displacement curves. Simulations prove that the method leads to satisfying results, but still remains unpredictive as the spring identified properties are only applicable for the specific tested configurations.*

*To cope with this issue, FEM*[5] *modelling methodologies are then developed, involving Smooth Particles Hydrodynamics and Lagrangian formulations. A Drucker-Prager material law which combines elastic-plastic behaviour with hydrodynamic coefficients is selected to model the soil behaviour. Bibliography analysis as well as influence studies on the element formulation and material parameters permit to define an appropriate dataset, which leads to convenient correlation with tests results.*

*The paper finally concludes on the suitability of standard specifications for soft soil crashes as well as the applicability of structural concepts developed mainly for crash on concrete. Besides, it addresses the feasibility of each simulation methodology, in terms of industrial application, and their capability to simulate correctly the physical phenomenon involved in soft soil impacts. It also raises their limitations and the complementary developments likely to assess the influence of horizontal velocity and friction effect.*

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[1] *DGA : Direction générale de l'armement*
[2] *MIL-STD : Military Standard*
[3] *DGA TA : DGA Techniques aéronautiques*
[4] *CEAT : Centre d'essais aéronautiques de Toulouse*
[5] *FEM : Finite Element Method*

# 1. INTRODUCTION

A previous Research & Technology program on helicopter crashworthiness underlined through a crash cases study that nearly half of helicopter accidents occurs on soft soil, that is to say earth, sand, snow and water. Therefore, a second program, devoted to helicopter crash behaviour improvement to be applied for future helicopter, was launched by DGA to study helicopter crashworthiness on soft soil, involving industry, laboratories and official services.

The structural collapse behaviour of an aircraft during an impact on ground is highly dependent upon the surface encountered; rigid surface impacts introduce concentrated loadings into the stiffest parts of the structures while water and soft soils impacts introduce distributed loadings over the fuselage skin. Moreover, in case of soft soil impacts, the soil potentially participates to the structure deceleration and the energy absorption (in the case of water, one even considers that most of the energy may be absorbed by the displacement of the water area around the impacting structure). Another remarkable difference stands in the fact that, in case of highly deformable soils, the landing gears no more (or very few) participate to the energy absorption, leading the structure and the impacted soil to withstand the full impact energy. As a result, significant structural response differences are likely to be produced when the impact surface is of soft soil or rigid type and structures designed for hard surface impacts may consequently no more offer optimum crash performances for soft soil impacts. Appropriate modelling techniques – depending on the soil nature, be they slightly (earth), moderately (sand, gravel) or highly (water) deformable – must therefore be applied.

On this basis, this paper aims at presenting firstly the study of crash cases of civil and military helicopters that occurred on soft soils. From the data gathered from the accidents reports, i.e. structure damages and end of flight description, speeds and attitudes at impact were evaluated in a simplified manner. This work was performed for both survivable and non survivable cases. Then, a focus was done on the speeds at impact of survivable crashes so as to compare them to the envelopes defined in MIL-STD, and the convenience of such standards or guidelines towards impacts on soft soil is commented. This paper deals only with the speed analysis, which provides the most interesting data.

The second part presents the drop tests performed at DGA TA in the frame of this program. Two kinds of tests were carried out. First, rigid specimens with shapes similar to helicopter parts were used so as to get data on the soil behaviour: water, earth and sand were tested. Secondly, elements of structure such as absorbers were dropped to check their performance towards impact on such surfaces. The data registered during the tests were then delivered to Eurocopter and ONERA for structure modelling. These two phases together allow a comparison between standards used to build crashworthy helicopters and the behaviour towards soft soil impacts they may have.

Finally, the present paper focuses on the development of methodologies to simulate vertical impacts of rigid and deformable structures on sand and earth, at several velocities from 2m/s up to 10m/s. Different solutions are implemented with the explicit FEM code RADIOSS, and evaluated by comparison with tests performed at DGA TA. These tests include impacts of rigid specimens which allow identifying the soil parameters, and impacts of flexible specimens which permit to validate the fluid-structure interaction.

In a first step, a macro-modelling method is investigated for sand impact, in which the interaction with the soil is modelled by non linear calibrated springs whose properties are identified from experimental load-displacement curves. Simulations prove that the method leads to satisfying results, but still remains unpredictive as the identified spring properties are only applicable for the specific tested configurations. To cope with this issue, FEM modelling methodologies are then developed, involving on the one hand Smooth Particles Hydrodynamics for sand impact, and on the other hand an advanced Hexahedron mesh for earth, both combined with a Drucker-Prager material law. Bibliography analysis as well as influence studies on the element formulation and material parameters permit to define an appropriate dataset, which leads to convenient correlation with tests results.

# 2. CRASH CASES STUDY

The purpose of this study was to evaluate the convenience of the design standards used for crashworthiness helicopter manufacturing and so to check that such standard still covers 95% of survivable crash cases when these occurred on soft soils. First, reminders of the survivability definition of MIL-STD 1290 are given. Then, the crash cases study process and results are presented.

## 2.1. Survivability Definition and Consideration

In Aircraft Crash Survivable Design Guide (ACSDG, ref. [1]), a survivable accident is defined as follows:

"An accident in which the forces transmitted to the occupant through his seat and restrain system do not exceed the limits of human tolerance and in which the structure in the occupant's immediate environment remains substantially intact to the extent that a livable volume is provided for the occupants throughout the crash sequence."

Two other parameters shall also be taken into account in the sizing of the aircraft. The first one is to sustain the heavy mass equipments in order to avoid every fall of the mechanical parts onto the passengers. The second one deals with the limitation of fire risks after the crash. To conclude, including survivability in the design and the sizing of a helicopter must insure a level of protection so that all the in-occupants can escape the aircraft after the crash. This means that the following conditions have to be respected:

- respect of a survivable environment,
- limitation of loads and accelerations transmitted to in occupants,
- sustain of heavy masses,
- limitation of fire possibilities after crash.

## 2.2. MIL-STD 1290 Impact Conditions

In this paragraph the impact conditions from MIL-STD 1290 of 1974 and 1988 editions (ref. [2] and [3]) are reminded. The cases defined in these specifications enable to cover 95% of the survivable cases studied in the frame of their creation, so that the improvement of aircraft survivability was economically and technically feasible as stated in [1]. Of course, the analysis performed during the study does not deal with all the impact conditions defined there, since only soft soil impacts are considered. Thus, conditions related to impacts on horizontal surface are relevant.

The Table 1 next page presents the MIL-STD 1290 impact speeds condition from 1974, with the evolutions included in the 1988 edition. The most noticeable change between these two revisions of the specifications is the replacement of the combined case envelope (lateral, longitudinal, vertical) by a "high angle combined case", which seems more realistic. Indeed, in this study and in the former one, crash cases with clearly identified lateral velocity are very remote with only one case. Nevertheless, an envelope of combined cases, i.e. longitudinal plus vertical, in the low Vx area may have been also relevant, as shown in this paper later. It may be pointed out that soft soils are already addressed, but only for the "low angle combined case" and with a California Bearing Ratio of 2.5.

| Condition N° | Impact direction in the helicopter coordinate | Object impact | Velocity in m/s | Evolution in the 1988 edition |
|---|---|---|---|---|
| 1 | Longitudinal (cockpit) | Rigid vertical barrier | 4,5 | Velocity changed to 6m/s |
| 2 | Longitudinal (cabin) | | 12 | None |
| 3 | Vertical | Rigid horizontal surface | 12,8 | For the case of retracted landing gear, the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 7,9 m/s instead of 12,8m/s. |
| 4 | Lateral | Rigid horizontal surface | 9,1 | None |
| 5 | Combined<br>$\Delta Vx^2 + \Delta Vy^2 + \Delta Vz^2 = \Delta Vr^2$ | Rigid horizontal surface | $\Delta Vx < 15.2$<br>$\Delta Vy < 9.1$<br>$\Delta Vz < 12.8$<br>$\Delta Vr = 15.2$ | Crash case changed to high angle combined case :<br>Vertical : 12,8m/s<br>Longitudinal : 8,2m/s<br>Besides, for the case of retracted landing gear the seat and airframe combination shall have a vertical crash impact design velocity change capability of at least 7,9 m/s instead of 12,8m/s. |
| 6 | Combined low angle<br>- Vertical<br>- Longitudinal | Plowed soil | 4.3<br>30.6 | None |

**Table 1 :** ***Crashworthiness specifications of MIL STD 1290 (1974 and 1988 editions)***

## 2.3. Study Presentation

### *2.3.1. Analysis Process*

The objective is to associate to each accident the impact conditions in term of speed (following the three axes) and attitudes (pitch, roll and yaw) based on the data written in the investigation reports.

For each accident, civil or military, an investigation is led by a commission in order to determine the causes and then the responsibilities, but not necessarily the impact conditions. Moreover, the aircraft are not equipped with a flight recorder; the data coming from the pilots about these parameters may be altered by the personal feelings that are sometimes far from reality. Nevertheless, all these elements enable establishing a first evaluation of the accident scenario. Therefore, it may be precised that the values chosen for the study remain, for the main part of them, estimated data.

In order to validate the data found thanks to the investigation reports, DGA TA decided, in the first study (ref. [4]) to rely on the results of two crash tests performed on two different helicopters. In the first test a vertical speed of 8.5 m/s led to a clear tail boom break at the junction with the fuse and to high deformations at the cone level. In the second one, a 5.7 m/s impact conditions provoked the tear of the tail boom and the break of the skids.

This analysis helped to find the following criteria to apply to check the vertical velocity estimation, when damages description or pictures of the helicopters are available:

- deformation of the tail boom ⇨ Impact speed = 4 m/s
- tear of the tail boom ⇨ Impact speed = 6 m/s
- failure of the tail boom ⇨ Impact speed = 8 m/s

This logic was kept for the presented study since the purpose was not to have the exact speeds for each accident, but to try to extract tendencies. Another point is that the study focuses on the survivable cases that should present vertical speeds close to these ones.

### *2.3.2. Analysis of each accident*

For each accident, a standard datasheet was established. It gathers all elementary information that is necessary to use the database, and gives the necessary information to evaluate the crash conditions.

A synthesis of the data is then established in order to evaluate the impact conditions. To ease the use of the data, the impacted surfaces are classified in groups: water, earth (sometimes with a distinction between hard or loose), snow, sand.

### *2.3.3. Data Treatment*

First, a global approach was done on the different characteristics of the accidents. From all the data collected, different (Vx;Vz) graphs were plotted, in order to show the tendencies. Then, particular points are studied in detail to find if they should be kept in the analysis or not.

Secondly, plots giving (Vx;Vz) per soil type were done. In fact, earth and sand accidents are plotted together, but in two separate diagrams in order to study the landing gear type influence. Impacts on water are drawn on one graph.

As the number of cases showing a lateral velocity is very low, no analysis on this parameter was possible. Moreover, this parameter is the most difficult to evaluate and is barely mentioned in the investigation reports. This is taken into account only for particular cases.

The data gathered here do not allow extracting tendencies on attitudes, like in the first study [4], and this is why attitudes are only used to study specific cases when needed.

## 2.4. Accidents General Characteristics

The purpose here is to identify the survivable accidents, to determine the impacted soil and then to remove survivable cases with too particular circumstances.

### *2.4.1. Overview*

85 crashes were studied here. Table 2 below sums up them and already shows their criticality.

| | | **Number** | **Number of passengers** | **Injured** | **Dead** |
|---|---|---|---|---|---|
| Accidents | Survivable | 61 | 216 | 47 | 0 |
| | Non Survivable | 24 | 84 | 12 | 72 |

**Table 2 :** ***Synthesis of analysed accidents***

Survivable accidents represent 72% of the cases. Among 216 passengers involved, 47 were injured. In the first study [4], which took into account every kind of soil including concrete, 79% of accidents were survivable. This statistic shows that the common idea of the less critical aspect of a crash on a soft soil may be put into question.

### *2.4.2. Impacted Soils*

Table 3 presents the type of soil impacted depending on the aircraft and gives the percentage of cases per soil type. In one case, the surface was identified as soft, but could not be defined. This is why the total number of accidents here is 84 instead of 85.

| | **Earth** | **Water** | **Sand** | **Snow** |
|---|---|---|---|---|
| Total | 51 | 20 | 9 | 4 |
| Non survivable rate | 23.5% | 40.0% | 0% | 75% |

**Table 3 :** ***Overview of impacted soils***

From this table, it is noticeable that impacts on snow are very rare (4 cases over 84), so that it will not be possible to get a conclusion on such a soil. Moreover, 75% of accidents of those are not survivable. Impacts on other surfaces seem numerous enough to try to extract tendencies.

This table also stresses the criticality of impacts on water with 40% of cases that are not survivable. Furthermore, some survivable cases led to the death of survivor(s) when H/C or passengers were not equipped with suitable devices (emergency floatation system for example).

### *2.4.3. First Analysis: Check of Particular Conditions*

The figure presented in Appendix 1 shows all the crash cases that led to a speed at impact evaluation. It has to be precised that if a speed interval is noted in the datasheet, the highest value was taken into account. The green points represent the survivable cases whereas the red ones represent the non survivable cases. The orange dots correspond to survivable cases that were removed from the analysis because their conditions were assessed as too favourable or the survivability was considered as exceptional.

In order to have a first idea of the soft soil impacts criticality versus the specifications on concrete, MIL-STD 1290 speed diagrams are also plotted (1974 and 1988 editions). E stands for Extended landing gears and R for Retracted. Concerning the 1974 edition combined case, it was decided to plot it as an ellipse, without taking into account the lateral velocity. This is coherent with the fact that the number of accidents identified with a lateral velocity is very low. Therefore, the envelope defined by this case can be expressed as follows:

$$\left(\Delta Vx \middle/ \Delta Vx^{\max}\right)^2 + \left(\Delta Vz \middle/ \Delta Vz^{\max}\right)^2 \leq 1$$

Hypotheses on maximum speed values are the same as the one described in chapter §2.2.

This plot shows the criticality of impacts with high sinking speed on every kind of surface. The transition between survivability and non survivability is obviously between 8 m/s and 15 m/s. Unfortunately, there are only few points available. In the high Vx area, it already appears that the low angle combined case from MIL STD 1290 (yellow dot) will cover a high number of survivable cases on soft surfaces.

## 2.5. Impacts Per Soil Type

Due to the lack of data concerning impact on sand, these cases are analysed together with impact on earth. Therefore, only two different categories will be dealt with in this analysis, earth plus sand and water.

### *2.5.1. Impacts on Earth and Sand*

Earth represents the most impacted surface with 60% of the accidents. Despite the amount of data (51 cases), it is not possible to classify these accidents by hardness of soil, as this parameter is barely given in the investigation reports (27%). Making statistics on so few cases will not provide enough evidence to get tendencies.

Concerning sand impact, nine cases were originally analysed but two were removed following the global analysis, so that only seven cases remain, all survivable. In ref [1], the possible significant role of the landing gear type, i.e. skids or wheels, is underlined since the contact surface at the impact is different. The larger the surface is, the higher the soil energy absorption may be. Thus, the analysis here is done per landing gear type. Only the survivable cases are plotted.

Helicopters with skids

51 accidents occur on helicopters equipped with skids landing gears in this study; among these cases, 43 impacts were on earth or sand. Figure 1 next page presents the survivable

cases (34) kept for the envelope evaluation after the global analysis. Some points are merged on the graph because the impact conditions were evaluated the same.

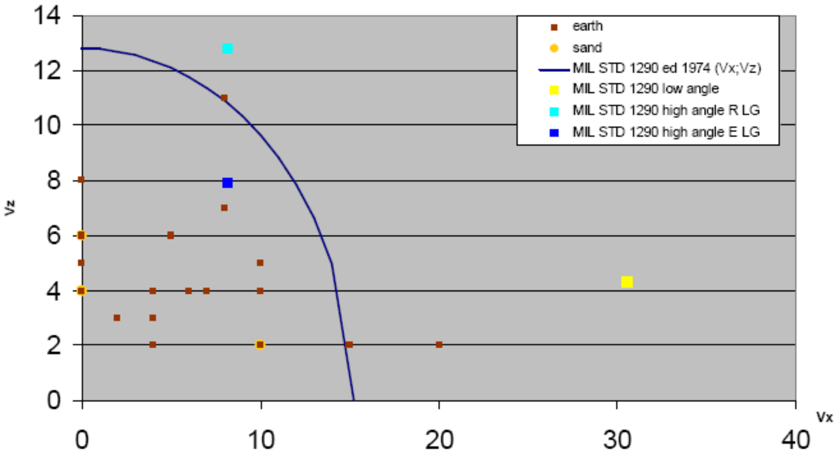


**Figure 1 :** ***Survivable impacts on earth and sand for H/C with skids***

Helicopters with wheels

34 accidents occur on helicopters equipped with landing gears with wheels, among which 17 happened on earth or sand. Figure 2 below presents the survivable cases kept for the envelope evaluation after the global analysis. As in Figure 1, some points are merged on the graph because the impact conditions are the same.

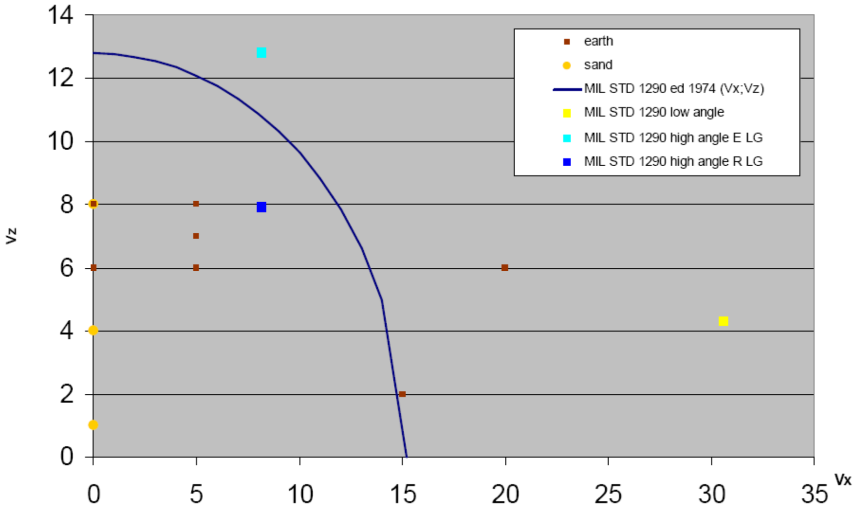


**Figure 2 :** ***Survivable impacts on earth and sand for H/C with wheels***

Discussion

No noticeable difference can be highlighted between the two types of landing gear. This may be due to the lack of data in the [low Vx, high Vz] area of the diagrams where the energy absorption of the soil, and so the influence of the contact surface, may have a greater impact. Indeed, with the low velocity at impact here, the contact surface difference may have been compensated by the shock absorber and the tyre deformation.

From these diagrams, it is clear that the low and high angle combined cases from the MIL-STD edition 1988 may cover most of the survivable cases on earth and sand, even if we miss data in the [low Vx, high Vz] area.

### 2.5.2. Water Impacts

From 20 cases, only 15 reports allow to define impact conditions. The other 5 accidents were not survivable. Moreover, one accident, considered as survivable, led to the death of 2 passengers by drowning. This statistic stresses the high criticality of impacts on water surface, with a 40% rate of non survivable cases. With the removal of two accidents in the global analysis, only 9 survivable accidents remain. Here, Figure 3 presents kept survivable cases and the non survivable ones. The lack of data in the low Vx area is more obvious than in the global analysis shown in Appendix 1: the maximum estimated sinking speed is 6 m/s for survivable case whereas the minimum one for non survivable case is 20 m/s. No border can be defined.

In the high Vx area, we have four survivable accidents:

- case 26 (20;2) occurs with a 5° nose up and an 45° roll attitude. This attitude puts this accident outside the envelopes defined in the MIL.
- accident 21 (25;1.5), the H/C was in a 5° nose up and 10° yaw attitude.
- accident 34 occurs in a level attitude.
- accident 16 is more surprising and cannot be completely compared to accident 51, which is not survivable. Vz may have been overestimated. One passenger was jettisoned and the two others managed to escape the helicopter. Finally, by comparing this case to other impacts on water, it may be considered as an exception.

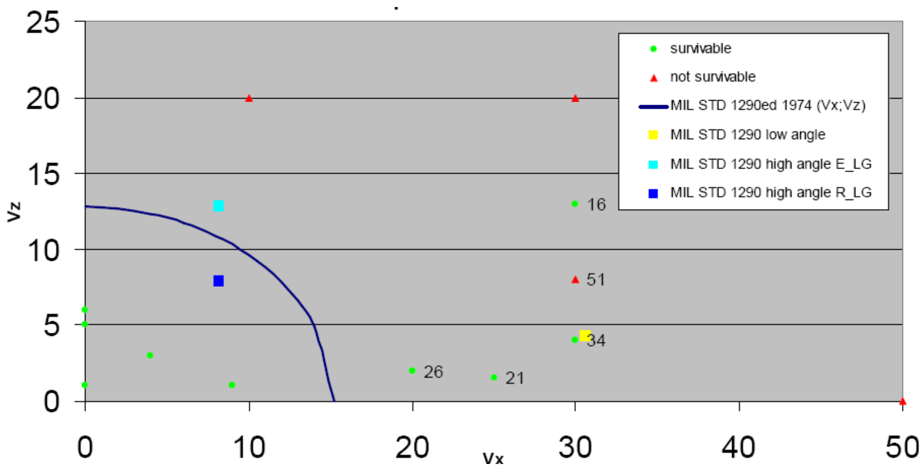


**Figure 3 :** ***Impacts on water***

<u>Discussion</u>

As precised above, impacts on water surface lead to 40% of non survivable cases. From the available parameters we manage to evaluate, no conclusion can be given in the low Vx area of the diagram. In the high Vx part, it seems that a condition close to the low angle combined case, but with a higher range for roll and pitch attitude, may be applied in order to cover a high percentage of survivable cases.

# 3. DROP TESTS

Once the suitability of the specification checked, another important point to verify is that the design details used to improve survivability within the specified envelope on hard soils work properly on soft ones.

## 3.1. Test Campaign Presentation and Aim

Static and dynamic tests were performed by DGA TA to characterise such kind of soils (soft soils and water impacts) in order to model their influence on shock absorbers crash behaviour. The test program consisted then in two steps:

- preliminary tests on 4 rigid specimens, to characterise the soil without any influence of the structure. Results will be used to correlate simulation models by adjusting soft soils material parameters.
- advanced tests on 3 flexible components to evaluate the fluid-structure interaction.

Three different soft soils were tested:

- Water,
- Normalised Fontainebleau sand since many bibliographic characteristics could be found in literature,
- Earth: in order to guaranty the reproducibility of the tests, it is important to choose a non clayey earth soil, with very low water content. Therefore, it would be easier to control the moisture and the mechanical characteristics of the soil.

Static tests were used to determine the mechanical characteristics of the soil. For that purpose, a cone penetrometre was used on sand and earth before each test; Furthermore, oedometric tests have been performed on earth and the average shear angle of sand was measured with an inclinometer. Nothing was required for water.

The dynamic tests were principally used to verify that the static characteristics coming from the oedometric tests are also suitable to model dynamic behaviour. They consisted in drop tests with vertical guidance, at different impact speeds and for different specimens (rigid and deformable). The concept is to fix the test article (rigid or deformable specimens with additional test masses) to the test rig in a horizontal position. The test rig is then released to let the test article fall down inside a pool full of soft soil.

Eurocopter provided the set of deformable specimens while DGA TA manufactured the rigid specimens and set up the whole instrumentation. The test specimens were equipped with the following measuring devices:

- Accelerometers in vertical direction and in 3 directions (up to 1000g),
- Pressure transducers on specimens and inside the pool,
- Effort sensors between the test specimen and the additional mass,
- Strain gauges.

## 3.2. Test Rig Description

During the drop tests, the specimens were guided by cables in order to enter in contact with the soil at a correct roll and pitch angles. The guiding frame is described hereafter in Figure 4. An accelerometer with a 5g calibration was put on the guiding frame in order to get the impact speed. Load sensors are positioned between the specimen and the ballast fixed to the guiding frame. The weight of the ballast is adapted for each specimen in order to have a falling structure weight in agreement with the test program.

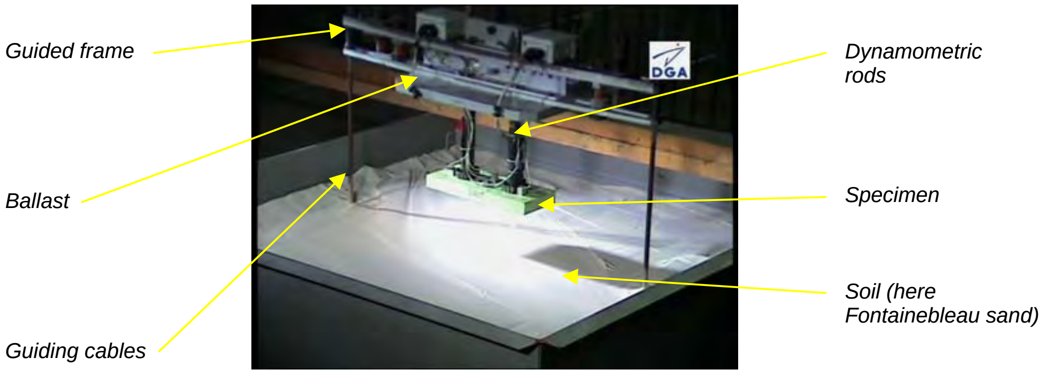


**Figure 4 :** ***Drop Test Guiding Device***

### 3.3. Specimens and test program

Four types of rigid specimens were dropped in order to get data on the soil behaviour; they are depicted in Figure 5 below. The shapes were chosen so as to be similar to features that may be found on French Armies Helicopters and that may impact the ground during a crash. Besides, three types of deformable specimens were tested: flexible tubes, an equipped tire and composite made crash absorbers (sinus beams).

The test program consisted in 18 tests on both earth and sand, and 17 tests on water with impact velocities from 2m/s up to 10m/s. The speed chosen for sinus beams, combined with the weight, lead to the same level of energy as the one they were designed for in the scope of rigid soil impacts.

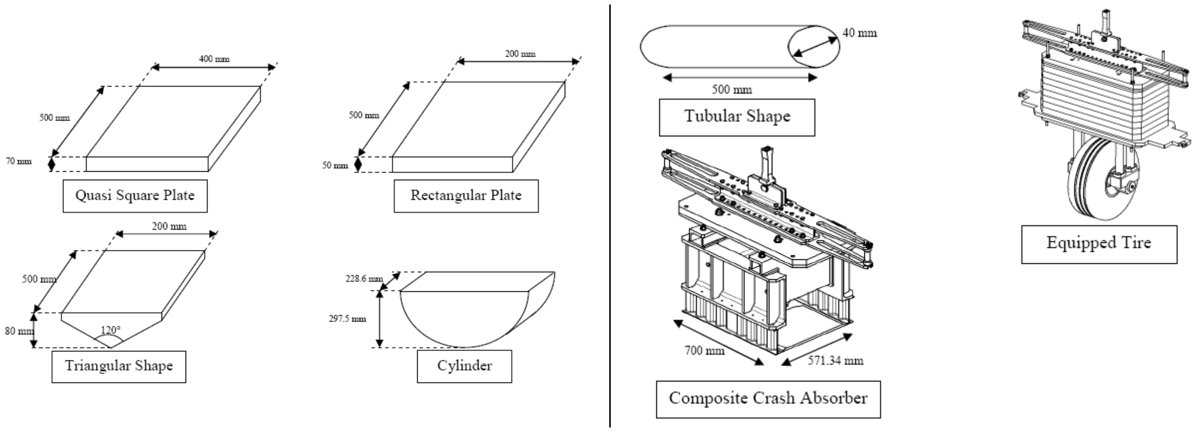


**Figure 5 :** ***Overview of the Rigid (on the right) and Deformable Specimens (on the left)***

## 3.4. Results and discussion

Since the purpose of this paper is not to present all the results, this paragraph shows examples of acceleration data gathered during the tests, which feed the discussion on the soils behaviours observations.

### *3.4.1. Rigid specimens drop tests*

Impacts on water are characterised by a low duration acceleration peak occurring when the specimen “breaks the surface”. Then, the deceleration is low as it is mainly due to hydrodynamic drag. Since the specimen speed is not reduced enough, it impacts the bottom of the pool with a still important speed. This is the cause of the second peak, as presented beneath.

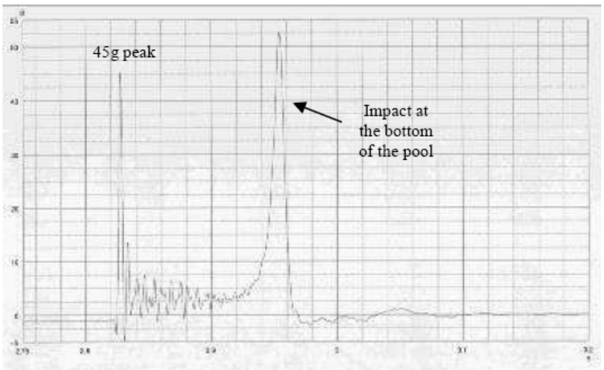


**Figure 6 :** ***Acceleration of a quasi square plate, impact at 10m/s on water***

For impacts on earth and sand, one can notice first an acceleration peak and then a short plateau corresponding to the soil energy absorption during its compression. Examples are given below for impacts of a quasi square plate on sand at 10 m/s and on earth at 6 m/s. It is noticeable that for an equal speed at impact, the specimen hitting water is submitted to a five times lower peak of acceleration than when impacting sand.

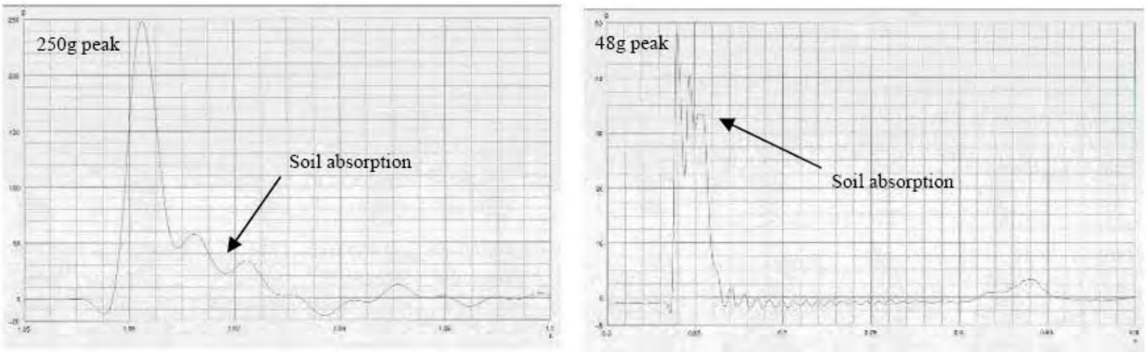


**Figure 7 :** ***Acceleration of a quasi square plate, impact at 10m/s on sand (left) and at 6m/s earth (right)***

### *3.4.2.Sinus beams drop tests*

The most interesting results are for sinus beams tests on sand and earth (see Figure 8). They are presented next page with the acceleration measured at impact. For both impacts, there is a deceleration similar to the one noticed on rigid specimens, but the plateau is there linked to the soil and the absorbers. But the absorbers did not work properly and the specimen broke far before the end of their normal absorption. This phenomenon was analysed by calculation.

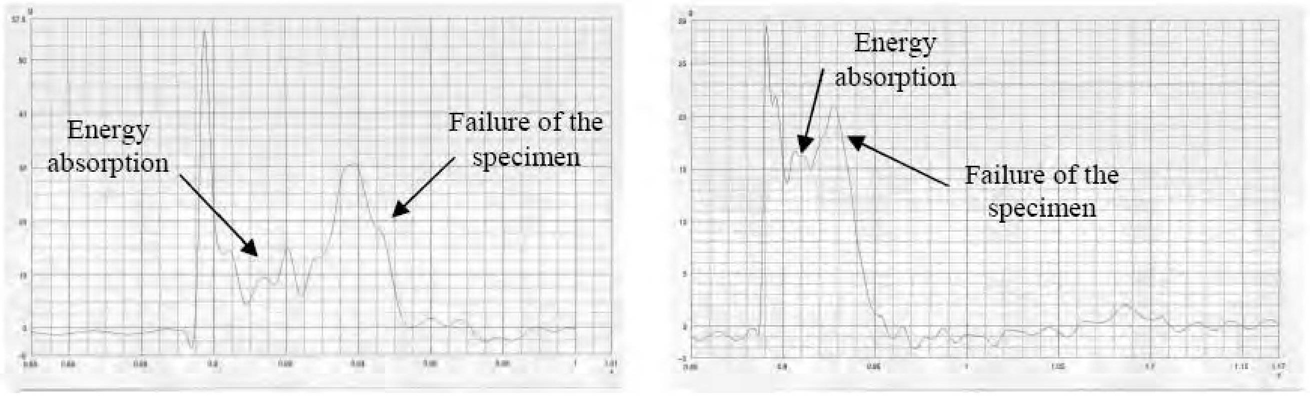


**Figure 8 :** ***Acceleration of sinus beams, impact at 8.6m/s on sand (left) and on earth (right)***

### *3.4.3. Discussion*

From the results of the study, and particularly from the ones presented here, it is clear that the soil behaviour may have a negative impact on the crashworthiness since a soil energy absorption may lead to a malfunction of the absorbers and then to higher loads or accelerations transmitted to passengers. Then, a special care may be given to these design details so as to get an equivalent crashworthiness on soft soils and on rigid surfaces.

# 4. MODELLING of SAND IMPACTS

## 4.1. Methodology

Two different methodologies were used to model sand impacts with the dynamic code RADIOSS: the first one is based on non linear springs whose compression law is determined from tests of rigid specimens, and the second one consists in a full Finite Element approach with Smooth Hydrodynamics Particles.

## 4.2. Macroscopic approach with non linear springs

The first step consists in exploiting impact tests results of rigid specimens, by plotting the measured load in function of soil penetration. The graph below shows that the shape of the load-displacement curves is similar for the different impact speeds, with a preliminary linear behaviour (initial stiffness) up to a peak load. A second load re-increase is also observed, whose maximum amplitude varies according to the impact energy and which is systematically reached at the same impact time, whatever the impacting shape and velocity. Such a phenomenon is likely to be generated by oscillations of the upper – deformable - test rig which is not considered in the simulations.

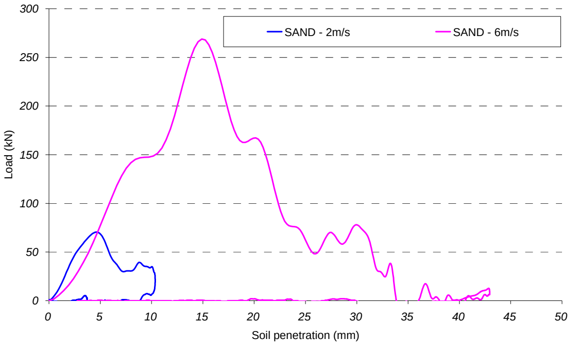


**Figure 9:** ***Load-displacement curves for rectangular plate impact on sand***

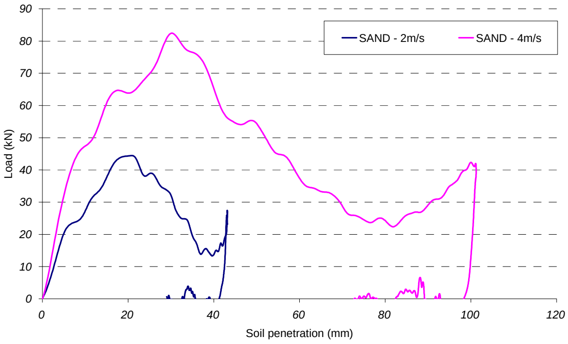


**Figure 10:** ***Load-displacement curves for cylinder impact on sand***

On that basis, the sand could be represented by a set of non linear springs working in parallel, for which a tabulated load-displacement law could be determined in accordance with test results. They are connected (same nodes) to a deformable surface with a null material to get the soil penetration shape. The load-displacement curve is calculated thanks to the tests results depending on the number of springs which are modelled by RADIOSS SPR_BEAM (type 13) properties. This type of spring element works as beam element with six independent modes of deformation: traction/compression, torsion, bending (two modes) and shear (two modes). In this case, only the compression mode is activated while the other degrees of freedom are blocked thanks to an infinite stiffness. A common contact interface (Type 7) is also set between the impactor and the deformable surface, with a stiffness coefficient determined according to the Young's modulus of their materials. Therefore, the following parameters have to be set: spring density, spring length, spring mass and inertias calculated to respect the time step criteria and spring compression law.

## 4.3. Application to flat rigid specimens

For a plate impact with null incidence, all the springs located below the specimen are acting in parallel with the same manner. Therefore, the calibrated tabulated law common to each spring is obtained by dividing the load-displacement curve of Figure 9 by the number of acting springs. The rigid impactor is besides modelled with brick elements tightened by a rigid body on which the residual mass, appropriate boundary conditions as well as gravity are applied. The correlation between test and simulation is satisfying, with an underestimation of -10% of the maximum acceleration after first impact and -4% of the maximum soil penetration.

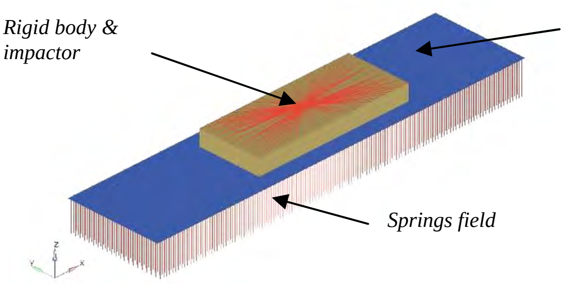


**Figure 11:** ***Model of rectangular plate for sand impact on springs field***

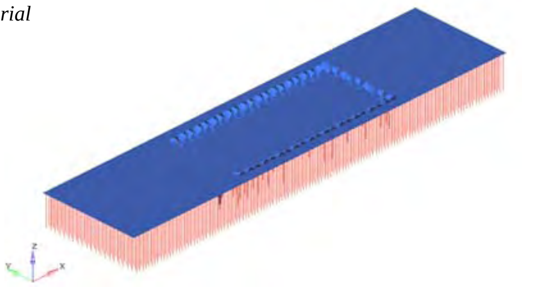


**Figure 12:** ***Final state for plate impact on sand at 2m/s***

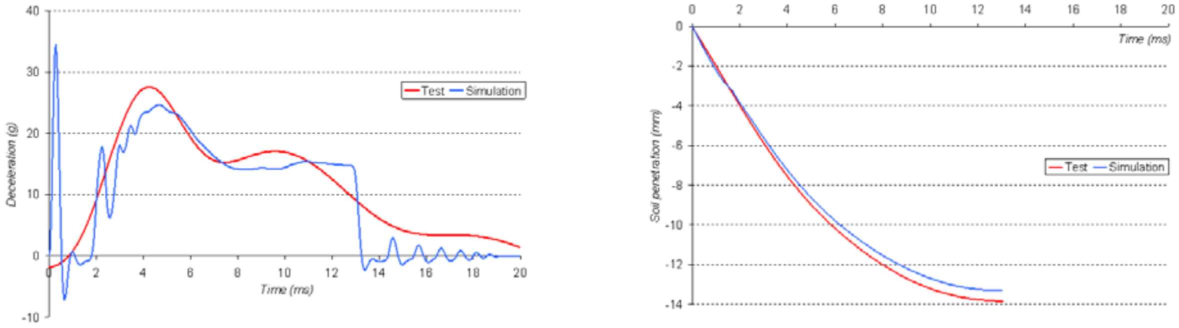


**Figure 13:** ***Results for plate impact on sand at 2m/s***
***(on the left, rig deceleration - on the right, rig vertical displacement)***

## 4.4. Application to curved rigid specimens

For a cylinder, it is obviously more difficult to determine the number of acting springs below the specimen than for flat specimens. Indeed, this number increases as the cylinder sinks into the soil, depending on its curvature. Consequently, the compression law must be determined for each spring and calculated with respect to the soil penetration. To simplify the problem, groups of "similar" springs are defined, for which iterative numerical trials are needed to find the most suitable compression laws. At last, the correlation between test and simulation is quite good, with less than 2% of error for the maximum deceleration value. However, the rebound is not well predicted, which leads to an overestimation of about 25% of final soil penetration.

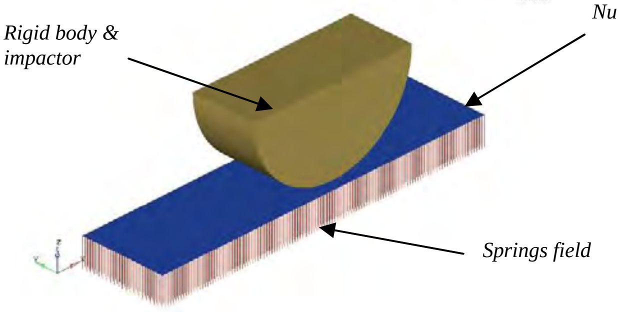


**Figure 14:** ***Model of cylinder for sand impact on springs field***

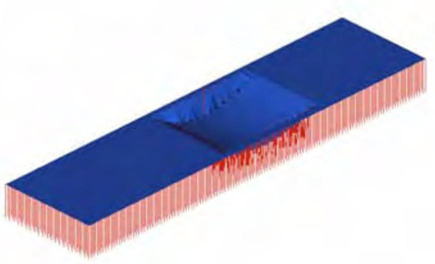


**Figure 15:** ***Final state for cylinder impact on sand at 2m/s***

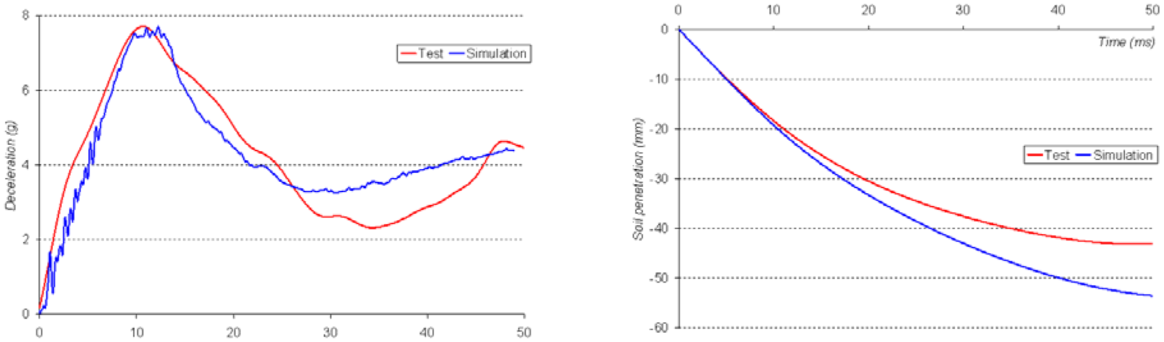


**Figure 16:** ***Results for cylinder impact on sand at 2m/s***
***(on the left, rig deceleration - on the right, rig vertical displacement)***

## 4.5. Advantages and limitations of macroscopic approach

This macro-modelling offers some advantages, especially in terms of CPU cost which allows many runs for influence studies. Nevertheless, this approach is not predictive since tests are required to set the appropriate compression laws of the springs. Besides, it does not seem suitable for complex shape, as the number of acting springs must be determined in function of time. To cope with these drawbacks, soft soils are now modelled by a DRUCKER-PRAGER material law associated with SPH formulation.

## 4.6. DRUCKER-PRAGER material description

Drucker-Prager laws available in the RADIOSS code (LAW10 or LAW21) are particularly well adapted for this kind of materials (see ref. [12]). It consists in:

- an elastic behaviour thanks to Young's modulus and Poisson coefficient.
- a plastic behaviour which links the second invariant of the deviatoric stress tensor $J_2$ and the pressure P thanks to 3 materials coefficients $A_0$, $A_1$, $A_2$. These parameters could be calculated from soil cohesion $\tau_0$ and soil friction $\phi$.
- an hydrodynamic behaviour which expresses the pressure P as a function of the variation of density $\mu$ thanks to the bulk modulus amongst other parameters.

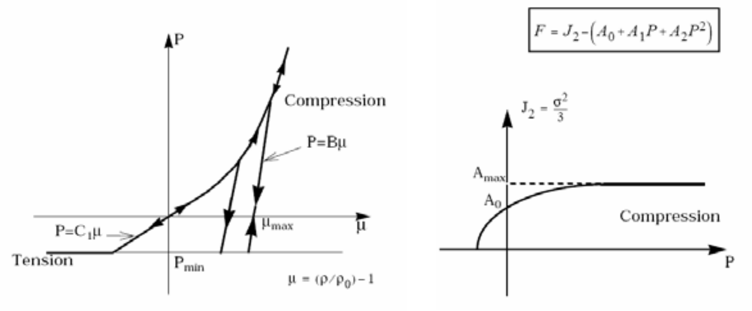


**Figure 17:** ***DRUCKER-PRAGER scheme in RADIOSS***

The DRUCKER-PRAGER law is mainly influenced by the following parameters that must be precisely evaluated: soil density, Young's Modulus, Poisson coefficient, Bulk modulus (directly linked to Young's modulus and Poisson coefficient), soil cohesion (linked to $A_0$ and $A_1$ parameters) and soil friction. For deviatoric behaviour law, static geotechnical parameters like material cohesion and internal friction angle must be identified from tri-axial tests for example. Equations of State (EOS or Hugoniot) parameters are generally issued from material shock polar or œdometric tests. Besides, sand cohesion is directly linked to the parameters $A_0$ and $A_1$ of the Drucker-Prager law. In our case, the material law parameters have been set according to DGA TA static tests, completed if necessary by a bibliography survey.

## 4.7. Mesh and SPH formulation

SPH is a meshless numerical method based on interpolation theory. It allows any function to be expressed in terms of its values at a set of disordered points so-called particles. SPH is not based on the particle physics theory. The conservation laws of continuum dynamics, in the form of partial differential equations, are transformed into integral equations through the use of kernel approximation. During the 1991-1995 period, SPH has become widely recognized and has been used extensively for fluid and solid mechanics type of applications. SPH method is implemented in RADIOSS in Lagrangian approach whereby the motion of a discrete number of particles is followed in time. It is recommended to distribute the particles through a hexagonal compact or a cubic net.

Under the impact area, sand has been modelled with SPH, in order to consider high deformations of soil during the impact, built from a center cubic net with a distance of 35mm between any particle and its closest neighbour. The total number of particles reaches 15139 for a particle mass of 15,5g. The size of the SPH net was chosen to set at least 6 cubic shape through the minimum dimension of the impactor. A second SPH net was also defined with a higher SPH density (h=20mm i.e. 5 times more particles than for h=35mm - 75615 particles instead of 15139). Simulation results were in the same range for both models, but with higher CPU cost with the finer density. Therefore, the size h=35mm is kept in the following analysis.

Outside the impact area, brick elements are used to save CPU time, with an element size growing from 35mm in the center to 100mm at the borders. A clamp condition is applied on the bottom and all the lateral faces of the brick mesh. The impactor velocity is applied as an initial condition to the master node of its rigid body. Gravity is applied to the whole model and 3 interfaces are implemented:

- A TYPE 2 (linking) interface to connect the 2 sections (SPH + bricks) of the sand media.
- A TYPE 7 interface to manage the contact between the impactor (Master) and the SPH (Slave).
- A TYPE 7 interface to manage the contact between all SPH (the slave particles of the interface TYPE 2 are excluded) and brick segments (Master surface of the interface TYPE 2). This interface is used to prevent SPH from penetrating inside the solid volume.

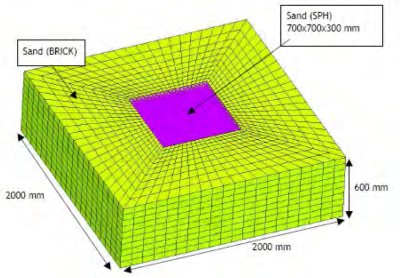


**Figure 18 :** ***Modelling of the sand pool with SPH and brick elements***

## 4.8. Application to rigid specimens

In a preliminary step, the influences of the sand cohesion parameter and the gravity are separately studied by simulating a rigid plate impacting sand at 10m/s. Simulations with or without cohesion give very close results, insofar the maximum peak acceleration is not influenced (the specimen is however more decelerated when cohesion is taken into account), leading to the conclusion that simulations without cohesion would be sufficient in case no accurate sand cohesion value could be determined. Simulations with or without gravity show that gravity influences the impactor velocity which decreases more slowly when it is not considered (gravity effects result in a compaction of the sand material). The application of gravity leading to the generation of an hydrodynamic field in the sand volume, an additional simulation is therefore performed to evaluate the required time to setup the pressure gradient in the sand volume (no impact, only the gravity field applied in the sand volume), and to clarify if a relaxation phase may be requested to establish the equilibrium in the sand before running the impact simulation. It proves that the gravity field is applied very quickly, since the pressure gradient can be established at around 2 ms: with respect to the total simulation time (more than 50 ms) and to the occurrence time of the acceleration peak in the DGA TA tests, one therefore considers that a primary simulation phase - with relaxation – is not strictly compulsory but will be more accurate.

Considering the above conclusions, RADIOSS simulations are finally performed without sand cohesion and with gravity effects, for the different impacting shapes. Results show that the correlation is quite satisfying for the dihedral specimen with correct initial stiffness and acceleration peak value. However, the correlation is less accurate for the rigid plate and cylinder, with simulated acceleration twice lower than in the tests, for all impact speeds.

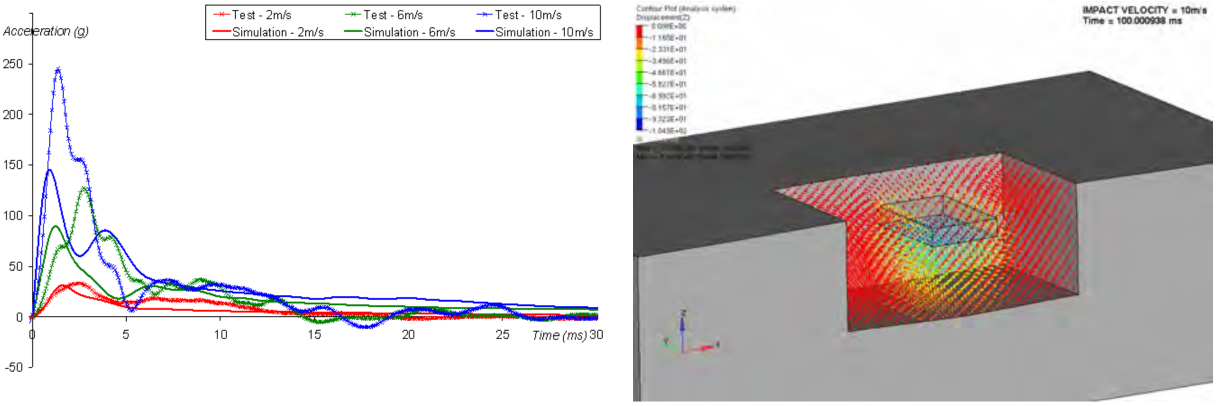


**Figure 19 :** ***Correlation of sand model – Rectangular plate at 2m/s, 6m/s and 10m/s***

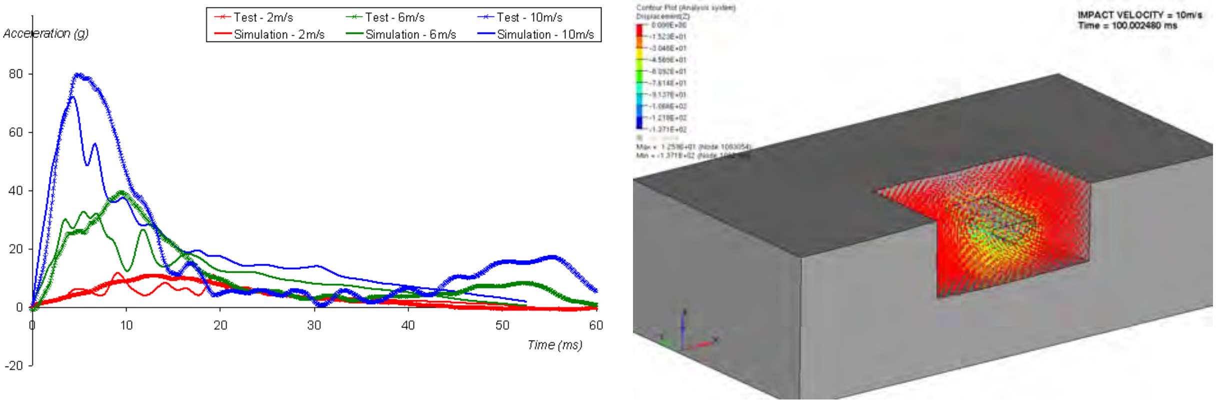


**Figure 20 :** ***Correlation of sand model – Cone at 2m/s, 6m/s and 10m/s***

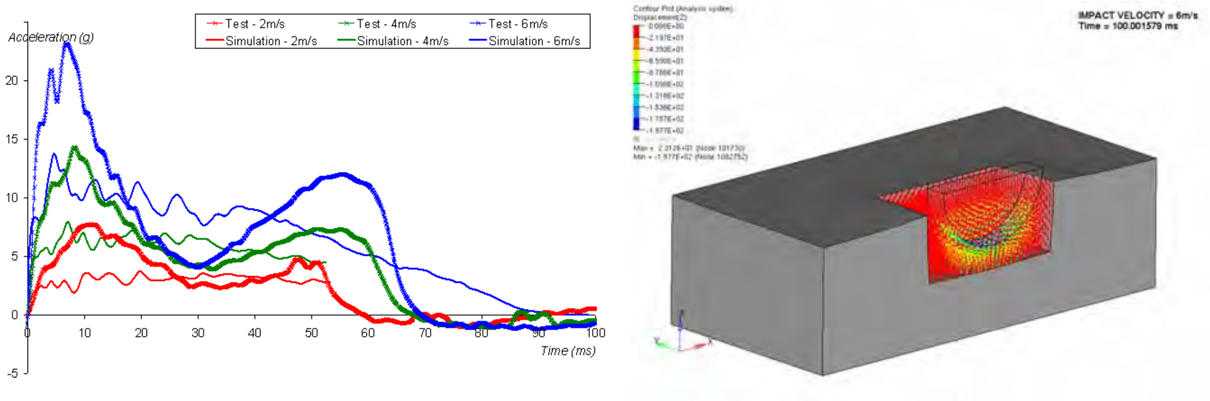


**Figure 21 :** ***Correlation of sand model – Rigid cylinder at 2m/s, 4m/s and 6m/s***

## 4.9. Application to flexible specimens

A fully flexible RADIOSS model of the main Tiger tire was developed in RADIOSS; it consists in about 35000 bricks and 20000 shell elements implemented with linear elastic, hyper-elastic and orthotropic material laws. An airbag is also used to inflate the tire at the appropriate pressure. According to the DGA TA test campaign, this model is dropped with an initial velocity of 4m/s over the sand SPH pool. The comparison between simulated and measured rig acceleration demonstrates the same level of correlation than for the rigid cylinder presented in §4.8, with -40% of error.

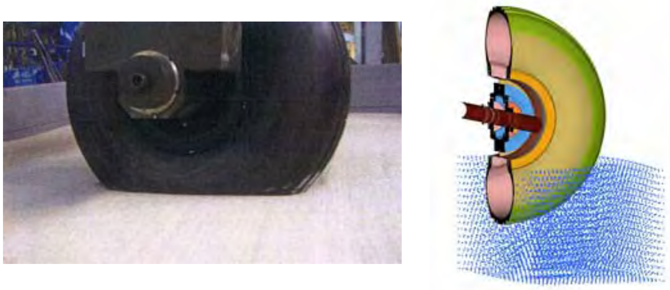


**Figure 22:** ***Final state of wheel impact on sand at 4m/s (Left = test – Right = Simulation)***

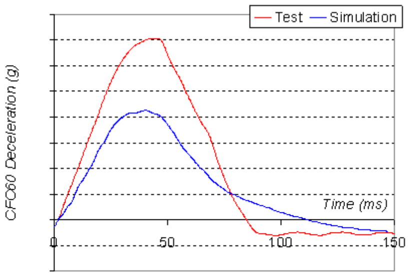


**Figure 23:** ***Comparison between test and simulation - Acceleration profile at 4m/s***

# 5. MODELLING of EARTH IMPACTS

## 5.1. Mesh

The earth medium is modelled with 300 000 Lagrangian HEPH bricks (8-node linear elements with reduced integration point and physical stabilisation of hourglass modes – see RADIOSS manual /PROP/SOLID $I_{solid}$=24) with an average mesh size of 20x20x20 $mm^3$. Two types of interfaces are used: a RADIOSS TYPE7 interface that manages the contact between slave nodes and master segment, and a RADIOSS TYPE11 interface that manages an edge to edge contact. For the main tests, a half model is created with the appropriate boundary conditions to reduce CPU costs. The simulation of drop tests is finally performed in two run phases since gravity is worth to be taken into account:

- Phase 1: The gravity and the dynamic relaxation are applied during 100 ms, to obtain a balanced soil under gravity (DYREL card in RADIOSS engine manual). This duration corresponds to at least 4 times the highest natural period of the soil system.
- Phase 2: The falling down phase with an initial velocity along Z vertical axis is performed. The total simulation duration depends on the test.

## 5.2. Influence studies

### *5.2.1.Soil Hugoniot: P=f(μ) sensitivity*

The aim of this analysis is to quantify the influence of the P = f(μ) relation parameters on the soil response, with respect to the potential variation of the properties of the earth actually implemented during the testing campaign. Indeed, the earth at DGA TA may not be strictly representative of a natural soil, as it was first extracted from natural ground - the material thus possibly lost some cohesion - and was then artificially packed in the pool. The cone index measurements made during the test campaign thus clearly showed discrepancies in the soil pressure not only along the pool depth (measurements revealed in a way a “weak” surface and “stiffer” layers just below), but also from one test to another.

In that goal, simulations of rectangular rigid plate impacts on earth are performed with two different bilinear forms for P=f(μ) relation:

- The “reference” is the one coming from bibliography, with a bulk modulus equal to 200MPa corresponding to the initial slope of the P= f(μ) relation.
- The “parametric option” consists in an initial stiffness equal to 5MPa which is divided by 40 compared to the reference case.

Comparison of both simulations highlights strong sensitivity of soil behaviour to Hugoniot parameters, in terms of acceleration and load (see Figure 24). Notably, the decrease of the first peak is numerically possible by tuning P = f(μ) parameters, even though this could lead to parameters sets which will not be consistent anymore with bibliographic values. Nevertheless, taking into account that the tested earth did not correspond to any “standard” soil, such calibrations might be considered to find the best set of values for P=f(μ) relation to fit test results.

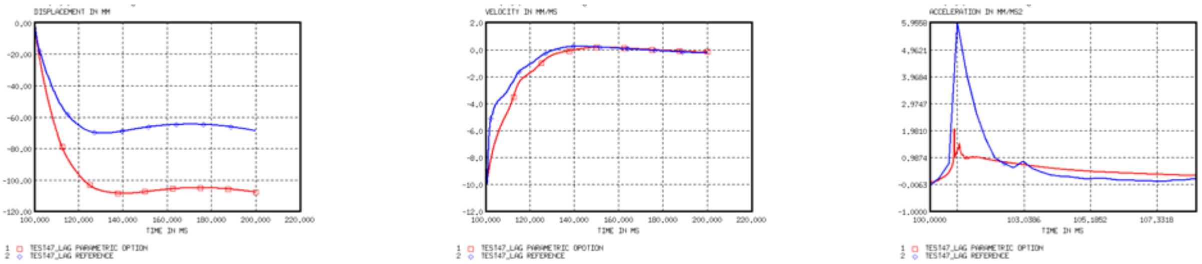


**Figure 24:** ***Influence of soil Hugoniot parameters on soil displacement, velocity and acceleration***

### 5.2.2. Calibration of P=f($\mu$) relation

Several runs were performed to define the best set of parameters values to correlate the rectangular plates test results at 10m/s. The P=f($\mu$) relation is still considered as bi-linear and the most influence parameters are $\mu_1$ and $P_1$ which define the initial bulk modulus $K_1$. It appears that:

- Increasing $\mu_1$ leads to lowering the peak load and increasing soil penetration. This is logical because the bulk modulus $K_1$ is set about 100 times lower than $K_2$. Therefore, this will delay the pressure increase and thus soil hardening.
- In the same manner, a high value of $P_1$ limits soil penetration, and tends to increase the loads.

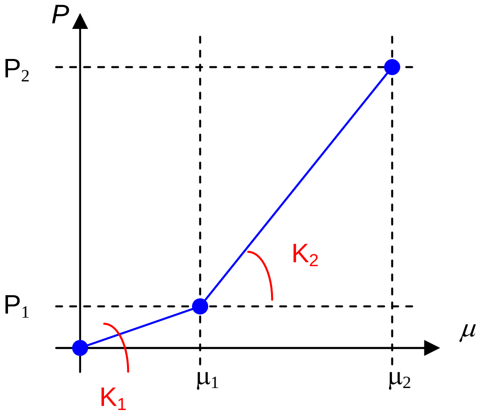


**Figure 25 :** ***Bi-linear P=f($\mu$) relation for earth material***

Firstly, a value of $\mu_1$ is selected to obtain a correlated measure of peak load. On this basis, several values of $P_1$ are then evaluated to find the most suitable soil penetration.

## 5.3. Application to rigid specimens

The P=f($\mu$) relation, calibrated to fit with the rectangular plate results at 10m/s, is directly applied on all the other cases available for rigid specimens. Globally speaking, the load-displacement curves are well predicted by the simulation, respecting the peak-plateau profiles for the plates, and the more linear profiles for the cone and the cylinder. Besides, there is a major tendency to over-estimate the loads and under-estimate the maximum soil penetration.

Such numerical/experimental deviations may first come from the variation of the soil properties, in its depth, as revealed by the static tests performed before each impact; this means that each layer of bricks in the simulation should have its own P=f($\mu$) relation to be more representative (which is obviously not feasible). Besides, the mean cone index varies between -11% and +13% amongst all the tests, and test center also mentioned a significant variation of earth humidity. All these remarks could therefore explain the discrepancies between simulation and test results, all the more amplified by the strong sensitivity of DRUCKER-PRAGER material parameters explained in §5.2.

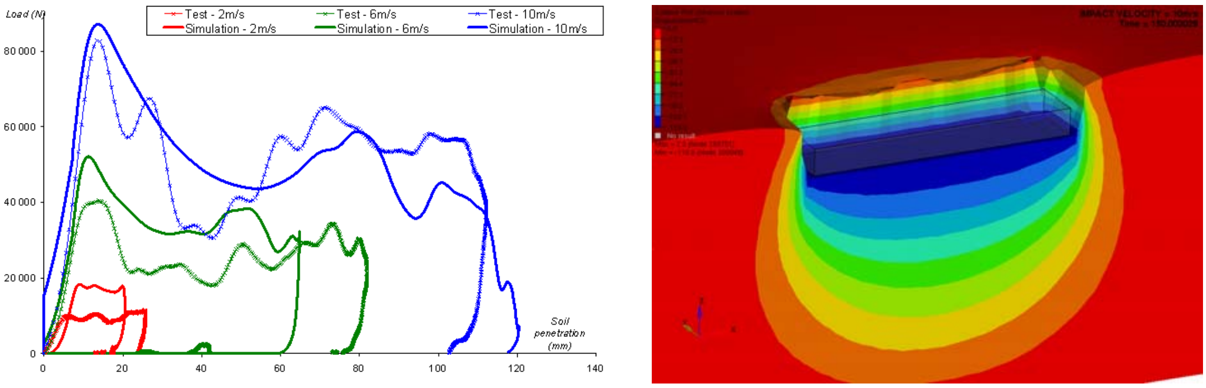


**Figure 26 :** ***Correlation of earth model – Rectangular plate at 2m/s, 6m/s and 10m/s***

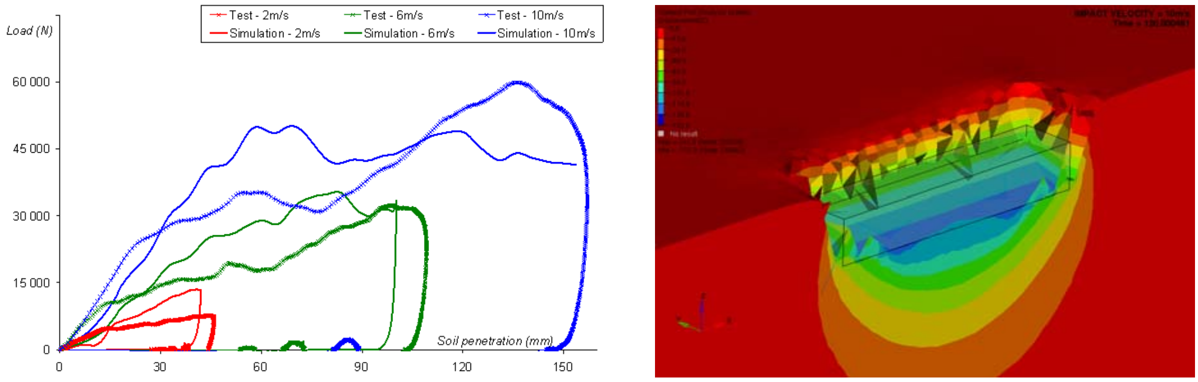


**Figure 27 :** ***Correlation of earth model – Cone at 2m/s, 6m/s and 10m/s***

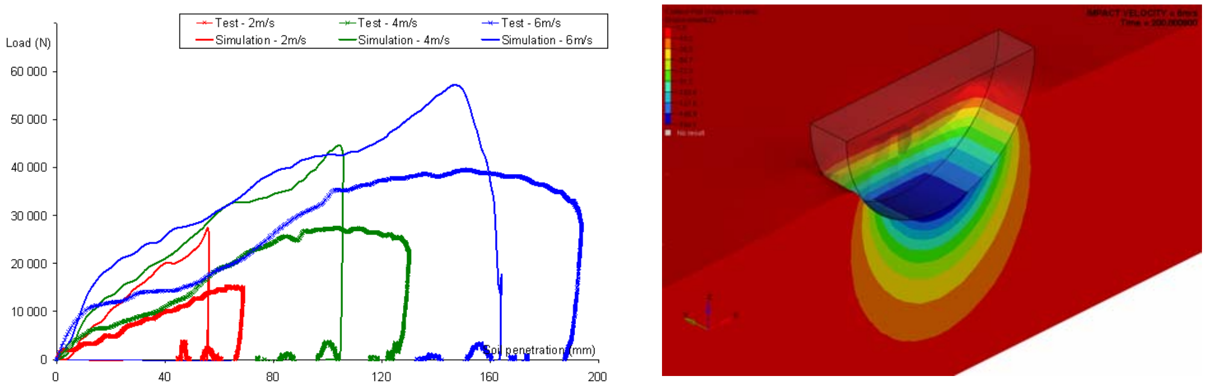
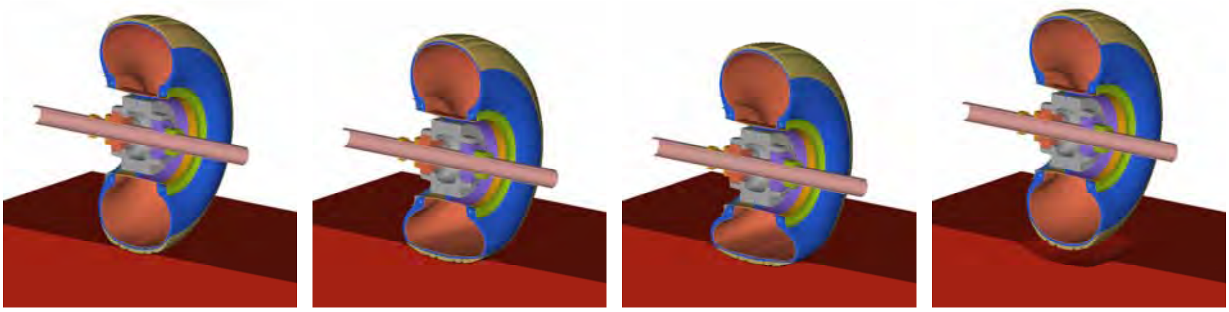


**Figure 28 :** ***Correlation of earth model – Rigid cylinder at 2m/s, 4m/s and 6m/s***

## 5.4. Application to flexible specimens

The RADIOSS model of the main Tiger wheel is now dropped at 2m/s over the earth Lagrangian pool described above. Results show a good correlation of the test rig displacement (less than 10% of deviation), but also an overestimation of the maximum load which reaches almost twice the value obtained during the test. Indeed, the material parameters were determined to fit the load-displacement curve of the specific impact at 10m/s of a rigid plate (see §5.2). The cone index measurement performed before both tests showed that the earth pressure was meanly 20% less important for the wheel drop test than for the rigid plate drop test. Therefore, the earth model was obviously too stiff in the simulation for the wheel than in the test, which could explain the discrepancy between simulated and measured loads.



*@10ms*

*@40ms*

*@70ms (maximum crushing)*

*@150ms (rebound)*

**Figure 29 :** ***Crash sequence of Main Tiger tire on earth at 2m/s by RADIOSS***

# 6. GENERAL CONCLUSION

This paper first presents a study of helicopter crashes on soft soils. From the three surfaces on which enough data were gathered (sand, earth and water), water is the most critical with a 40% non survivability rate. Furthermore, for several crashes on water considered as survivable, some survivors died because of drowning.

Then the speed at impacts were compared to the crash cases defined in the MIL-STD 1290 (editions 1974 and 1988) so as to check the suitability of such standards towards accidents on soft soils. The main conclusion is that using such specification to improve the crashworthiness on soft soil may allow covering a high rate of survivable accidents on earth and sand. The same conclusion may be applicable to water, but data on crashes on this surface are very rare so that a dedicated study on this surface shall be useful to better assess helicopter structures behaviour in these crash conditions.

Generally speaking, two main facts could be underlined based on investigation reports analysis:

- Data available in the low Vx part of the diagram are not numerous enough to find a clear border of the survivable envelope. So it seems difficult to challenge the vertical speed of 12.8 m/s recommended in the standards.
- A design that takes into account low angle impacts (high Vx; low Vz) would allow covering a high rate of survivable accidents. Such impact condition is prescribed in MIL and ACSDG but only for plowed soil with a 2.5 CBR.

Following this, analyses per type of soil confirm this tendency and show that an extension to soft soil of the low angle combined condition should improve survivability for impacts on earth and sand. Furthermore, this kind of impacts also occurs on water, but this condition should be reworked because of the non efficiency of the landing gears. Furthermore, as data on water impacts are rare whereas such accidents are often critical, a dedicated study on this surface shall be useful to better assess helicopter structures behaviour in these crash conditions.

In a second part, an overview of the tests performed to check the behaviour of soils and structural details is given. First, drop tests performed on rigid samples gave data on the soils behaviours, showing that earth and sand absorb some energy whereas an impact on water leads to a high acceleration peak and then a slow down of the specimen.

Then, tests on deformable samples allow checking the impact of the soil energy absorption on the elements used to improve helicopters crashworthiness. They highlight the fact that designing crashworthy for soft soils may lead to take care about absorbers configuration and trigger load. In conclusion, crashes on soft soils are not always less critical than on rigid ones and can even be worst. Concerning survivability envelopes, the ones defined in MIL STD are in good agreement with the data extracted from the accidents study, even if additional points are needed to conclude it definitely. For crashworthy design consideration, water should be treated as a particular case. Regarding earth and sand, energy absorption devices developed for crashes on rigid surfaces may lose part of their efficiency, but this could be compensated by the energy absorbed by the soil itself instead of the absorbers. Therefore, a special care shall be given to make them work properly on these surfaces, especially about their integration in the structure and about their trigger load.

Besides, this study shows that drop tests of rigid and deformable structures on soft soils require adequate measurements and accurate test conditions. Indeed, the impact tests performed at DGA TA on sand and earth reveal the difficulty to have reproducible phenomena, especially because of the strong influence on material behaviour of soil packing and surrounding humidity. This scattering could deeply influence the correlation level of simulations.

Several FE methodologies have been developed in RADIOSS to model soft soil impacts. In a first phase, non linear calibrated springs were used to simulate the compression behaviour of sand during the impact. Their laws were determined thanks to tests results, and are thus dependant on the impactor geometry, incidence angle and impact speed. The method offers good correlation with tests and very low CPU time, but cannot be used for prediction purposes.

In a second phase, FEM methods were investigated, based on Hexahedron mesh and SPH models, associated with a DRUCKER-PRAGER material law whose parameters have been defined thanks to DGA TA tests, completed if necessary by literature survey. Works first showed that the effect of gravity was worth to be considered, in order to account for the compaction effect. For the considered impact configuration, it however appeared that a preliminary relaxation phase may not always required, as the equilibrium of the hydrodynamic load field generated by the gravity is established in a short period compared to the impact duration.

For sand impacts, influence studies were carried out to quantify the influence of different parameters, such as the material cohesion. It appeared that a similar numerical/experimental correlation was obtained, with or without cohesion. More generally, this correlation is considered satisfactory for sand impacts, as well in terms of velocity as of acceleration.

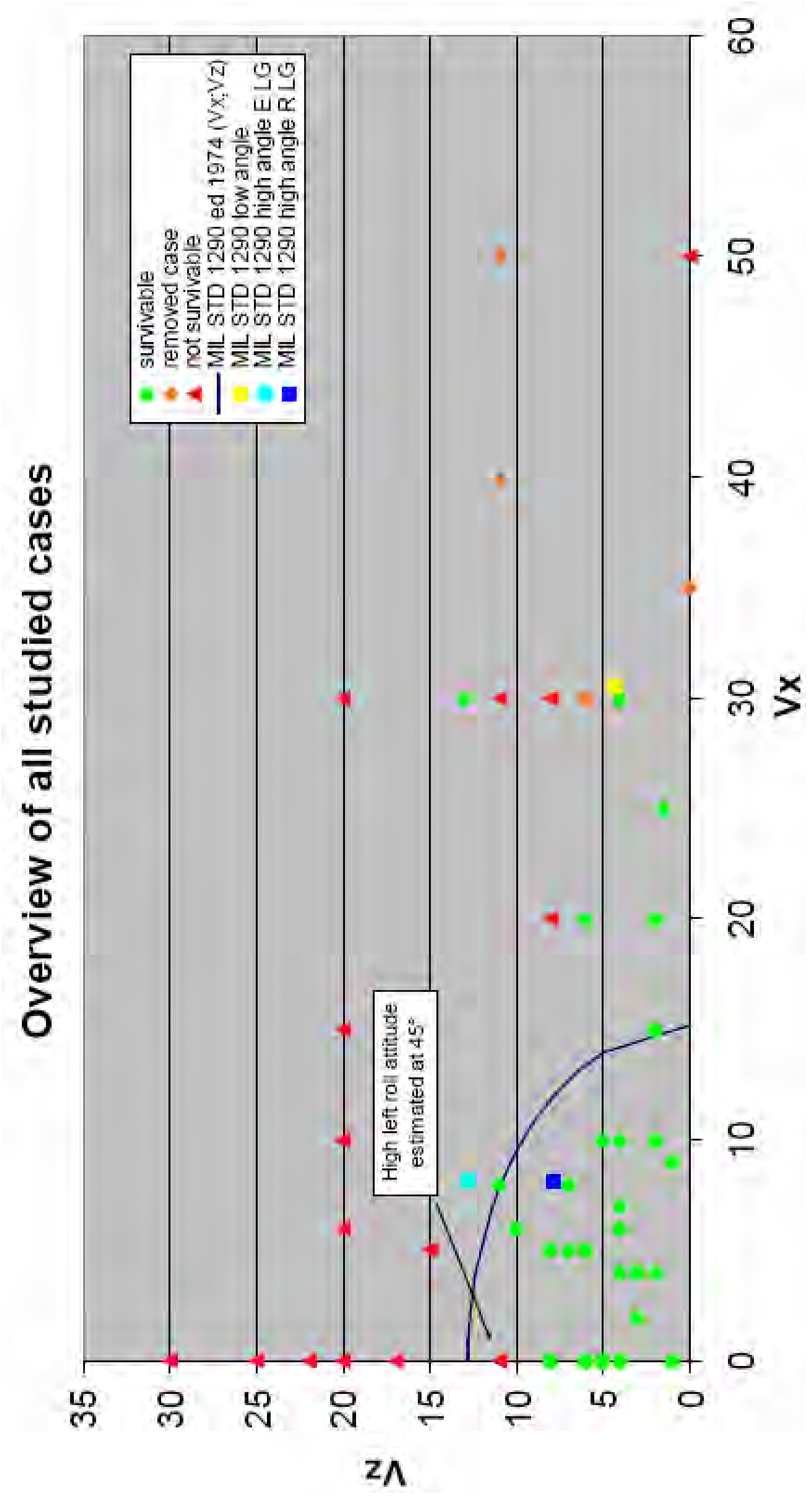
For earth impacts, the Hugoniot parameters have a strong influence on the soil behaviour, controlling both the peak load at the impact and the final soil penetration. Iterative runs were required to find the best set of parameters values to fit with test data because of the significant discrepancies in the earth packing and surrounding humidity. Despite this, the correlation between tests and simulations is also considered satisfactory.

As a general conclusion, one will note that validation works strongly rely on relevant and accurate tests results to determine material parameters, in order to ensure reliable correlation. Moreover, the present works mainly consider purely vertical impacts configurations, which are not representative of real helicopter accidents; most of the efforts in the future should therefore focus on the analysis of friction and horizontal velocity effects on soil behaviour, which could lead to roll and turn over. This will come together with a complete modelling of the helicopter, including the landing gears, flexible airframe and eventually crashworthy seats and dummies, which would permit to simulate more complex crash configurations on soft soil.

# 7. ACKNOWLEDGMENTS

Authors wish to acknowledge the French Ministry of Defence for their financial support, and also their sub-contractors who participate actively to the present work (EMA, Teuchos, SEGULA).

## 8. APPENDIX 1


Overview of all studied cases
Vz
Vx
0
5
10
15
20
25
30
35
0
10
20
30
40
50
60
survivable
removed case
not survivable
MIL STD 1290 ed 1974 (Vx;Vz)
MIL STD 1290 low angle
MIL STD 1290 high angle E LG
MIL STD 1290 high angle R LG
High left roll attitude estimated at 45°

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| | | |
|---|---|---|
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