# SHAKING TABLE TESTS ON SEMI-ACTIVE TUNED MASS AND TUNED LIQUID DAMPERS

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**ABSTRACT :**

One of the goals of the COVICOCEPAD project is to develop a mathematical model of tuned liquid dampers (TLD) devices. This new model will take into account the damping forces resisting the actions resulting from the viscous interactions between the liquid and its rigid container, the hydrodynamic head losses subsequent to orifices passing and the internal viscosity of the liquid. To calibrate the mathematical models full scale tests on shaking table are being performed. A performance evaluation of the TLD devices will be accomplished by the comparison between the behaviour of a specific structure with and without passive protection. This work addresses on the possibility of exploiting the liquid sloshing motion in tanks for specific vibration control purposes of civil engineering structures. Analytical, numerical and experimental issues are referred and the test steel frame is presented.

**KEYWORDS:** TLD, shaking table, passive control, vibration, damper

## 1. INTRODUCTION

The activities presented in this paper are being developed in the aim of the project COVICOCEPAD (Comparison of Vibration Control in Civil Engineering Using Passive and Active Dampers). Its leading purpose is to model the behaviour of semi-active devices of the TMD type (tuned mass dampers), developing also control algorithms for the optimisation of a complete structure including those semi-active devices. Additionally, this project intends to develop also a mathematical model of TLD type devices (tuned liquid dampers).

This new model will take into account the damping forces resisting the actions resulting from: (a) the viscous interactions between the liquid and its rigid container, (b) the hydrodynamic head losses subsequent to orifices passing and (c) the internal viscosity of the liquid.

In fact, the use of such alternative methodologies can be an indeed adequate solution to increase significantly a structure capacity to resist a strong earthquake. Passive protection devices, whose properties can be modified during their movements, are the main composition of these protection systems. The capacity of such devices to improve the dynamic behaviour of a structure being strongly dependent on the potential of their control algorithms.

Two partners of the COVICOCEPAD project are running important experimental dynamic equipment in Europe – the ELSA laboratory reaction wall, at the Ispra Joint Research Centre, in Italy, and the LNEC shaking tables testing hall, in Lisbon, Portugal. Hence, a performance evaluation of those devices will be also accomplished by comparing experimentally the behaviour of a specific structure with and without protection. It is a full-scale steel structure that will be also analysed to check its behaviour alterations when protected by different kinds of devices. This test specimen has a specific upper concrete slab, increasing its total weight up to about 10 tons, and was conceived for a previous benchmarking testing activity on the same shaking table and reaction wall being consequently suitable for both facilities.

## 2. STEEL FRAME

As previously referred, for another benchmarking testing activity on shaking tables and reactions walls [1,2] a specimen was already designed taking into account the characteristics of LNEC and ELSA facilities and so it will be used in the aim of this project.

The specimen has a linear behaviour, of course under the seismic inputs foreseen for this project, just one degree of freedom and it is modular in the sense that it is easy to dismount for transportation among the facilities involved in the project. If needed, it is also ready to accept different kinds of devices to be attached by means of an appropriately designed K bracing.

According to the design requirements, as illustrated in Figure 1, the specimen has a longitudinal size of 300 cm, a transverse size of 275 cm, a column height of 450 cm and an inter-storey height of 300 cm.

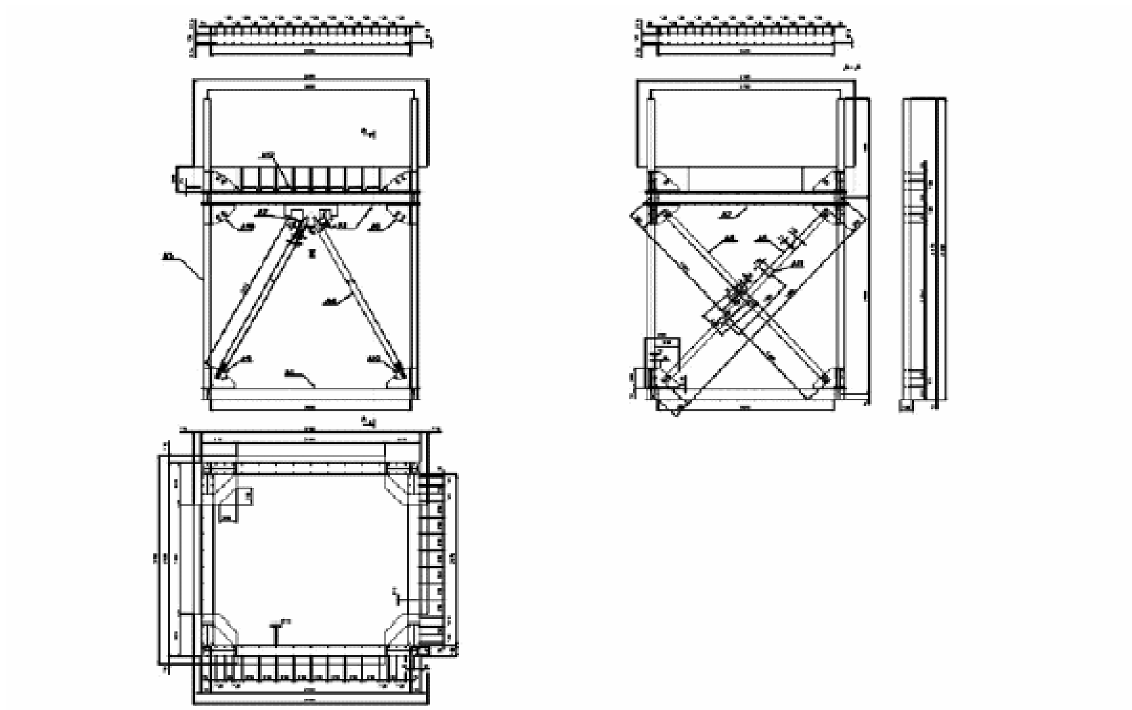


Figure 1. Plant, longitudinal and transverse profiles of the steel frame

The choice of the steel sections was based on the compromise between flexibility and maximum admissible displacements during the tests without damage. Thus, columns and beams were respectively chosen with HEB 100 and HEB 180 steel sections, the K and X braces with HEB 100 and UPN 100 sections, in the latter case the choice is imposed to allow the cross of the braces. Those X braces are used in the transverse direction to grant a large stiffness that isolates the dynamic response of the frame in the transverse direction from the longitudinal one.

The steel selected was of grade S355. After this first choice of main element steel sections, the frame was verified through an elastic analysis. The weight of the upper concrete slab, 8250 kg, was then chosen to make the total weight of the model close to 10 tons.

Figure 2 shows the steel structure during previous viscous fluid dampers tests performed at the Zografos Laboratory of Earthquake Engineering of the National Technical University of Athens.

Figure 2. Steel frame during previous tests

## 3. SEISMIC PROTECTION AND VIBRATION CONTROL SYSTEMS

It is commonly referred to as a seismic protection system, or vibration control system, a set of devices that, through their behaviour, increases the structures capacity to resist the seismic demands or reduces the vibration due to an external source. When the option to use seismic protection system is made, the goal is to reduce the forces and deformations caused by seismic actions through the modifications of the dynamic global behaviour of the structure, or through the increase in the energy dissipation capacity of all the assembles.

The seismic protection systems can be classified into three major groups: the passive, the active and the semi-active protection systems. The designation of passive systems refers to those which work without any energy supply. In contrast, the active and semi-active systems need energy supply for their normal behaviour.

In the recent years many technologies of passive had been developed, these passive systems being the type of seismic protection with more applications in the world [3]. This can be explained by its simplicity, reliability and easy to maintain. Examples of passive protection systems are the base isolation, the dampers, the TMD and the TLD.

TLD can be considered as very special TMD where the mass is replaced by a liquid tank or column. Despite the simplicity of the TLD components, the nonlinear dynamic behaviour of the liquid in the tank is complex to model. One of the goals of the COVICOCEPAD Project is to contribute for the analytical model definition of the TLD dynamic behaviour.

## 4. COMPUTATIONAL AND EXPERIMENTAL PROGRESS STUDIES ON THE USE OF TANKS AS TLDs

The risk of occurrence of severe structural damage or failures during a catastrophic event (eg. earthquakes and hurricanes) can be reduced by adopting vibration control techniques, which in most of the cases aim at increasing the damping characteristics of civil engineering structures.

Between the many vibration control devices devoted to increase the damping skill of the structure, TLD offer several advantages, including: low cost, easiness to install in existing structures and effectiveness even for small-vibrations [4,5,6,7,8].

The performance of TLD relies on the sloshing of liquid contained in partially filled tanks mounted on the structure, devoted to absorb and dissipate the vibration energy of the structure. The main action produced by liquid control devices essentially consists of the shear force caused by the inertia of the liquid mass, which if suitably tuned is able to cause a significant reduction of the structural response. Because of its peculiar character the evaluation of the performance, in terms of the energy dissipation, of a tuned liquid sloshing damper requires a comprehensive understanding of complex fluid-structure interactions, which has motivated a number of theoretical and experimental researches [7,9,10,11,12].

Theoretical models of liquid sloshing in TLD devices can be obtained either from a mechanical analogue, or from more exact analytical models of the structural and liquid domain. For the earlier, simplified formulations generally provide modelling of liquid sloshing in tanks, based on an equivalent mechanical analogy which uses lumped masses, lumped springs and dashpots to describe fluid motion; the lumped parameters characterizing the equivalent mechanical model are usually determined from the linear wave theory [7].

For the latter, more complex models require a complete mathematical description of the liquid motion and fluid/container interactions under dynamic conditions. Actually the reliable prediction of dynamic response of control devices based on fluid motion plays a central role for better understanding the real perspectives offered by TLD for applications in the field of intelligent structures, as regards to mitigation of earthquake and vibration hazards through vibration control [6,7,8].

In detail, some methodologies applied for analysis of the seismic behaviour of existing bottom supported storage tanks, under predominantly horizontal seismic actions were presented. As regards to modelling liquid motion in flexible metallic tanks, two FEM approaches were introduced earlier for the numerical analysis of the seismic response of liquid-filled tanks that also permit to determine design envelopes, through successfully validated software (Figure 3).

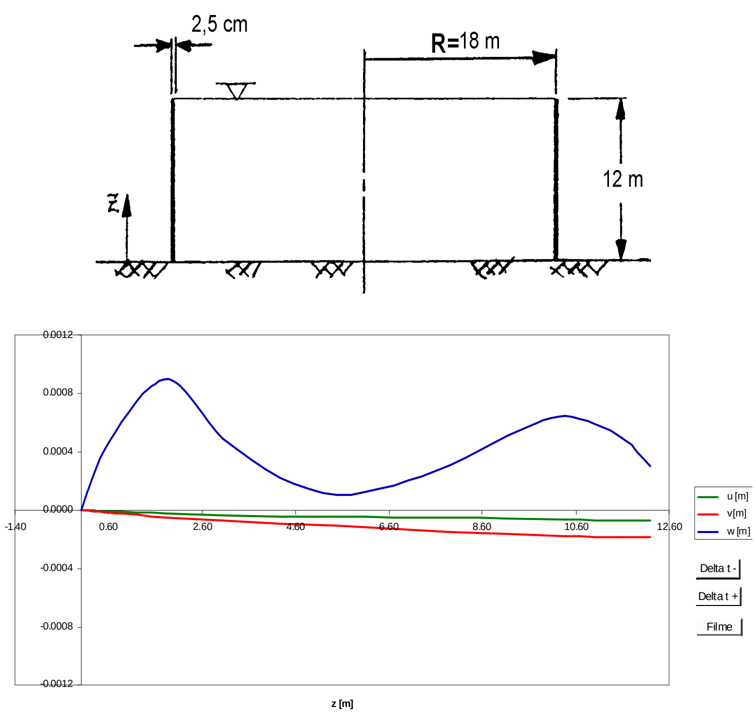



Figure 3 - Tank displacements response to Veletsos pulse, validating model and software.

The research indicated the need to obtain the responses of 10-14 artificial earthquakes, satisfying frequency requirements of the spectral density at the site, in order to determine quite accurate (relative errors below 3%) design envelopes of bottom supported tanks (Figure 4).

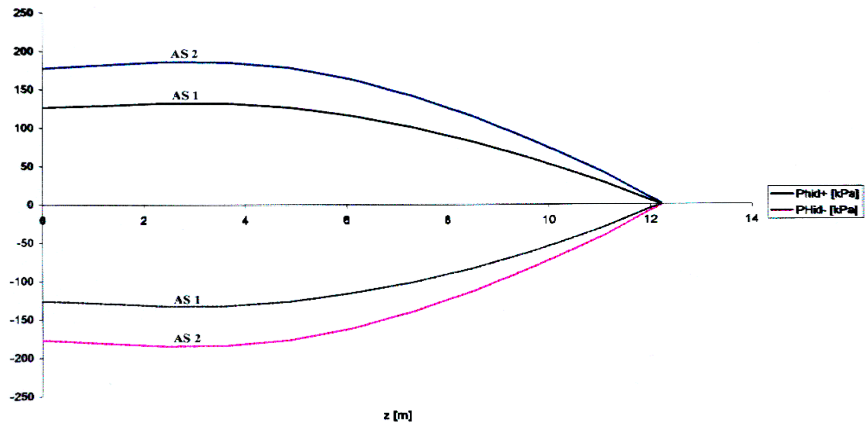



Figure 4: Envelope of hydrodynamic pressures in the reference tank (kPa).

One should consider that results from analytical developments on the above specific topic cover a branch of Lifeline Engineering as well, addressing the response, the design recommendations and the potential upgrading of existing or new bottom supported storage tanks (for: water, crude oil and energy derivatives, wine, chemicals) and pipelines, under seismic actions (predominantly horizontal) that can cause their total or partial non-functionality [7,10,11]. Therefore such mathematical treatment emphasizes its own importance and significance, independently from control of vibration applications.

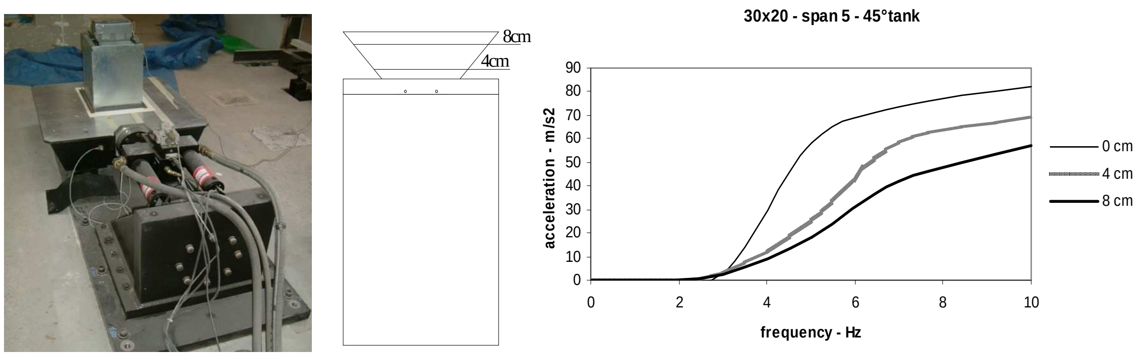
From an experimental point of view possible benefits, deriving from the application of liquid devices for attenuating the dynamic response of non-linear structural models with unilateral constraints, were investigated and published earlier [13,14,15]. Actually the full understanding of the device behaviour and fluid-container interactions is necessary for reliably analyzing and designing control devices based on liquid dissipation.

Moreover it has been reported earlier some results obtained by means of an experimental investigation developed on rigid blocks moving on a foundation base subjected to a horizontal forcing function and equipped with some rudimentary sloshing water devices.

Before defining the tests to be performed at the large 3D shaking table at LNEC, in Lisbon, experimental data derived by means of a small shaking table facility at the Laboratory of the University of Naples “Federico II”, in Italy, were accomplished. They were devoted to compare the dynamic response of blocks equipped or not with devices for various liquid levels of the tanks, in order to produce a first check of the possible effectiveness of such devices on rigid structural models exhibiting a non-linear behaviour under dynamic shaking (Figure 5).

To this regard, the need of predicting and preventing failures associated to rocking and overturning of rigid structures undergoing strong ground shaking have motivated a consistent number of studies on rocking response of rigid blocks.

This is basically due to two main reasons: on one side, a wide variety of structures can be collected in this model class; and, on the other side, dynamics of rigid blocks are pretty complex due to their intrinsic non-linearity, and can be considered a still open research topic. One should also consider that very few studies have been developed, to date, addressing the problems of coupling the TLD devices to rigid structures and of the evaluation of their potential effectiveness [14,15].




(a) (b) (c)

Figure 5: (a) Preliminary shaking table tests;
(b) Block equipped with trapezoidal (45°) TLD with marks at two liquid levels (4cm and 8cm);
(c) Acceleration results for 45° tank with different water levels.

## 5. CONCLUSIONS

This paper addressed among other aspects on the possibility of exploiting the liquid sloshing motion in tanks for specific vibration control purposes of civil engineering structures. Analytical, numerical and experimental issues were introduced earlier, giving a general overview of some studies developed (or in progress) by some of the authors on each specific topic.

As regards to modelling liquid motion in flexible metallic tanks, two FEM approaches were introduced earlier for the numerical analysis of the seismic response of liquid-filled tanks that also permit to determine design envelopes, through successfully validated software. The research indicated the need to obtain the responses of 10-14 artificial earthquakes, satisfying frequency requirements of the spectral density at the site, in order to determine quite accurate (relative errors below 3%) design envelopes of bottom supported tanks.

Moreover, from an experimental point of view, coupling of liquid devices prototypes with rigid structural models exhibiting non-linear behaviour under dynamic motion were investigated; although an already high number of studies have been produced in the research area, this special particular application has been rarely treated in the literature, so it can be considered of basic importance because it covers a wide variety of structural typologies. Experimental results allow appreciating potential effectiveness and reliability of liquid devices also for the specific cases studied.

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