SEISMIC EARLY WARNING SYSTEMS FOR STRATEGIC INFRASTRUCTURES AND CUHES

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ABSTRACT

The research activities described in this paper have been oriented to increase the capability of early detection and identification of extreme natural events of Geological, Atmospheric and Hydro-geological origin like earthquake, storms, floods and fires. The scope of this research[1] was to increase the protection of relevant Cultural Heritage goods or strategic infrastructures through the development of advanced monitoring technologies of Seismic Early Warning and new anti seismic devices activated by the SEW signals. A demonstration program with prototypical applications has defined to assess the paradigmatic architecture and standards for the innovative integration of different capability, technologies and disciplines to prove the operational effectiveness of the early protection for the selected relevant infrastructures and CUHES. The limit state verification of the structural response for existing or new constructions is a well defined task of the anti seismic standards and regulations. However, for some relevant strategic infrastructure and CUHES the serviceability level design should be inadequate with respect the absolute value of some relevant works of art, specially when is imperative to protect them against any, even small, damage to avoid catastrophic consequences or preserve to the future generations. The David of Michelangelo in Firenze, Italy is a typical example of "relevant" statue necessitating 100% seismic protection. Also some gas pipeline infrastructures could request the maximum level of seismic protection. The objective of this research is to study the possible configuration of Seismic Early Warning to protect those types of structures. The nesting of dedicated net of single-station monitoring systems for the selected infrastructures within the regional early warning sensors network is analyzed to activate the protection devices of a statue like the David of Michelangelo and the fire protection system of oil extraction fields and pipeline in Val D'Agri, Basilicata, Italy. A new dedicated system of devices to protect the "David di Michelangelo" based on the use of very low dissipative ceramic antiseismic devices activated by a SEW system has been developed.

KEYWORDS: Early Warning, ceramic seismic isolators, rocking, airbags for statues.

1. INTRODUCTION

To increase the protection capability for critical infrastructures and relevant cultural heritage assets and goods from risks and damages resulting from earthquakes, the development of advanced monitoring technologies, finalized to the early detection, identification and warning of extreme natural events of geological origin have been analyzed, in connection with the development of very low damped anti seismic devices, blocked in normal conditions and activated by the early warning triggering signal. The first obvious step to reduce the risks connected to natural events like earthquakes is to assess specific risk scenarios for each type of critical infrastructure or CUHE in order to plan the specific actions to manage the crises, both in the time and space scale:

a.) The time scale of the possible actions to reduce the risk can be spread along a time interval of decades for strategic/structural solutions, related to design the upgrading of the existing protection strategies; years (1-3 years) to adequate only the critical elements to the desired safety requirements (when needed); months for rapid structural interventions; weeks and days to manage the immediate post event scenarios and cleaning actions.

b.) the spatial scale of the interventions are generally at local and regional scale. The local scale relates the specific elements of the critical infrastructure or CUHE and the local management of the first interventions. They communicate with the regional and/or national public institutions managing the post crisis event.

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In this paper one of the primary objectives is the definition of a new step in the time scale of the possible actions to protect primary importance infrastructures and CUHE goods: the scale of seconds, through the possible actions activated by a warning signal from a network of sensors dedicated to the early detection and identification of the parameters univocally significant each of the critical event scenarios (e.g. earthquake) defined in a risk assessment analysis for the selected infrastructures.
At regional scale, a key point is the realization of one or more demonstration Control Centres which:

- build-up and maintain a robust, secure and interoperable communication systems based on improved supervisory control and data acquisition (SCADA) systems to support the awareness, command and control capabilities;
- ensure the maintenance and quality of the real-time sensor data acquisition;
- Inform the first technical responders for the rapid post event interventions (repair, clean, decontamination, etc...);
- support the research and develop of new innovative sensors for the capability detection and identification of environmental parameters;
- perform high formation in the fields of sensor developing, data acquisition and analysis, complex system interoperability , optimization processes;
- Support the communities and country administrators to minimize the impact of the possible events.

The early detection-identification, warning system and protection devices developed in this research can be independents or connected to the automatic protection systems to mitigate the effects. Often, in case of structures of historical or artistic interest the evaluation of the safety requirements is very difficult due to the complexity and singularity of the monument. In Italy, for architectural historic structures, the "Guidelines for evaluation and mitigation of the seismic risk to cultural heritage" defines, among the two classical limit states SLU (Last Limit State) and SLD (Limit State of Damage), a third state named SLA (Limit State of damage for works of Art like frescoes, museal objects, statues, etc.) which "during an earthquake of a certain level are submitted to modest damage and can be restored without significant loss of their cultural value". However, for some relevant strategic infrastructure and CUHES this level of protection against seismic risk should be inadequate with respect the absolute value of the monument, specially when is imperative to protect against any, even small, damage to avoid catastrophic consequences or preserve to the future generations. Furthermore in the Italian guidelines the SLD evaluation can be required also in local parts of the museum where artistic objects of absolute value are located. For specific structures (e.g. statues of primary importance) "the administrative competency may request a higher level of seismic protection, even in absence of structural damages". The David of Michelangelo in Firenze is a typical example of statue necessitating 100% seismic protection. A study of the CUHE sites in Italy with respect the seismic PGA zones map have been performed, identifying the distribution of two category of museum objects: a) Primary Importance, b) Relevant importance.

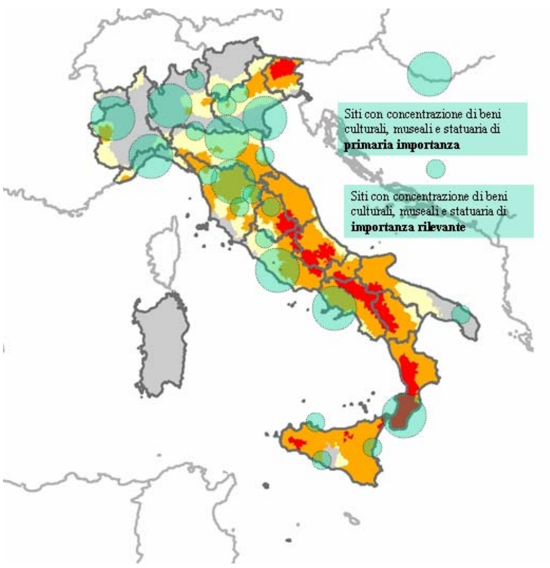

Figure 1: Concentration of the "Primary importance" and the "Relevant importance" CUHES in Italy.

The main part of the primary importance Historical structures are relatively far from the first category seismic zone (Zone 1) and a dedicated net of sensors nested within the regional network of SEW stations located on the seismogenetic faults should ensure a reasonable alert time to trigger the activation of anti seismic devices, which are blocked and non visible in normal conditions. The necessity to block the devices in the normal condition is due to their very low stiffness and dissipation to limit the force at the base of the work of art. A statue like the David of Michelangelo need to be protected against the rocking because some fractures occurs at the base of the legs and even the minimum expected ground acceleration could be extremely dangerous. The protection system "Earlyprot" developed by ENEA is compound by very low dissipation and very low stiffness ceramic devices, plus an anti seismic protection cage provided by special airbags to support the statue at the gravity centre. The devices and the cage with airbags are located beneath the basement floor, not visible by visitors, which can be activated together, in sequence or separately by the early warning signal. The intervention is not invasive, is compatible because made with materials available in the Michelangelo's epoca, and is reversible.

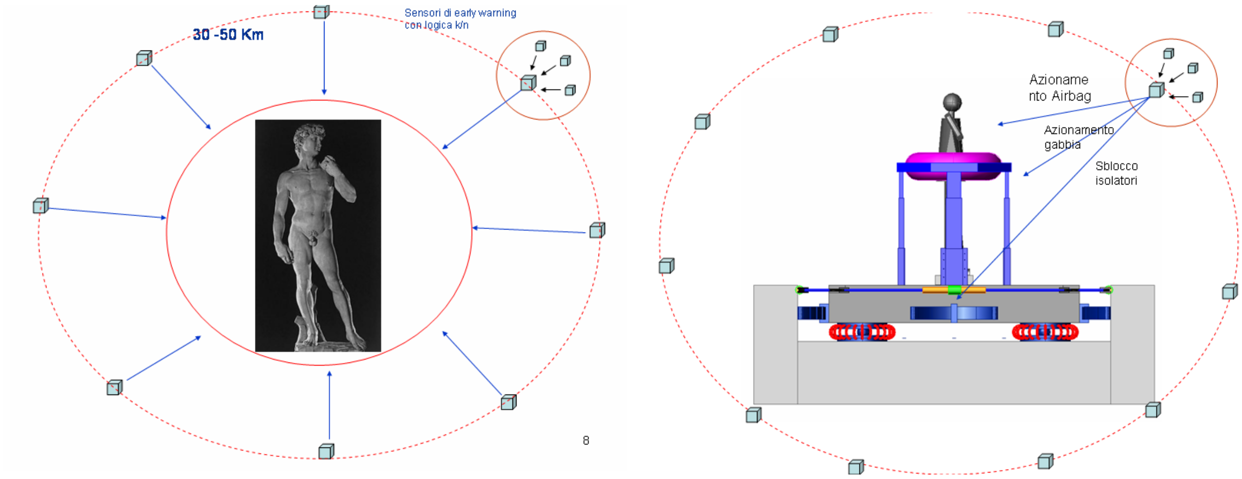

Figure 2: System "Early rot" activated by a dedicated SEW for the David of Michelangelo

2. EARLY ESTIMATION OF THE EARTHQUAKE INTENSITY

The proposed model must provide the primary level safety for the relevant CUHE goods and structures, acting the mitigation interventions few seconds before the event occurs or few seconds after the first significant sign of the occurring event (of natural or voluntary origin). The second level of safety need robustness and reliability of the control system according well defined and internationally accepted standards, being the replicability characteristic of the prototypical application one of requested needs. Namely, to achieve these characteristic the ISO/IEC27001 for processes and organization, and the ISO/IEC 15408 Common Criteria for informatics systems are applied. Exportable, robust, secure and interoperable telecommunication systems were together with significantly improved protection of supervisory control and data acquisition (SCADA) systems. A basic specific question relative to the early warning is if we can evaluate the earthquake intensity analyzing the first seconds of the seismic wave in the P_phase "Nakamura (1988)". In the present work the observable parameters of the time history during the first 4 seconds of the seismic wave detected in proximity of the seismic fault are:

i. The integral of the pseudo velocity spectrum of the first 4 seconds of the P_wave,
ii. The integral of the pseudo displacement spectrum;

and the fundamental period $\tau^P_{\max}$ of the first 4 seconds of the P_wave is defined by:

$$\tau_p^{\max} = 2 \cdot \pi \cdot \frac{\left(\int_{t1}^{t2} Sv \cdot d\tau \right)_{P\_wave}}{\left(\int_{t1}^{t2} Sd \cdot d\tau \right)_{P\_Wave}} \quad (1)$$

"Wu et all (2006)" used the integral of the squared velocity and squared displacement to define the fundamental period. Other approach by "Wu and kanamory (2005)" considers the displacement, velocity and acceleration peaks of the first 2 seconds of the P_wave to infer the PGD, PGV and PGA of the earthquake. To calibrate the regression between $\tau_{\max}^{P}$ and the magnitude, a numerical model developed by ENEA named Sa_Sew integrate the equation (1) to evaluate $\tau_{\max}^{P}$ using the Italian earthquakes time histories from the European Strong Motion data base. The following parameters are available by the software Sa_Sew analyzing the first 4 seconds of the Earthquake time history:

- modified Housner integral (HI) within the bandwidth T1-T2,
- displacement integral (HD),
- PGA of the P_wave and $\tau_{\max}^{P}$ (T_sew).

The linear regression between the dominant period of the first 4 sec. of the P_wave and the magnitude is obtained by SA_SEW analyzing the time history from the European Strong Motion Data base www.isesd.cv.ac.uk for Italy:

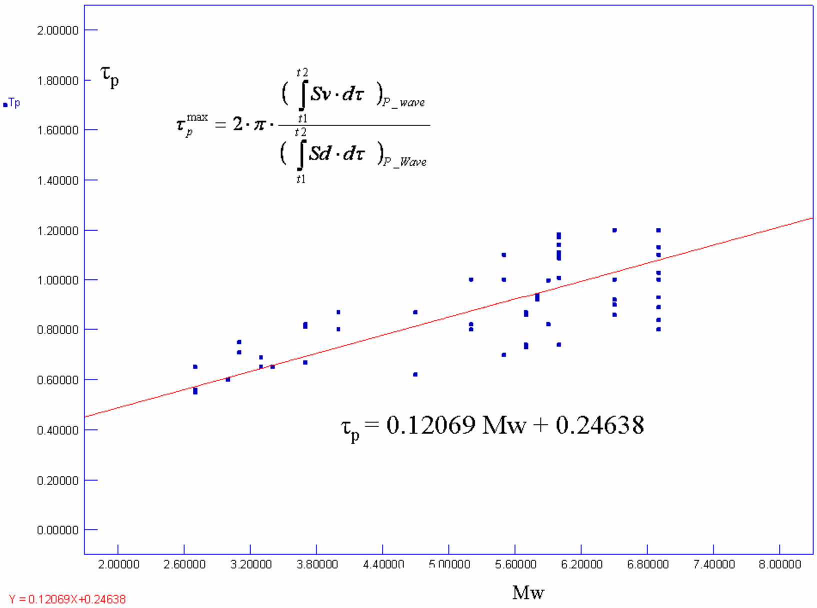

Figure 3: Linear regression between the dominant period of the first 4 seconds of the P_wave and the magnitude.

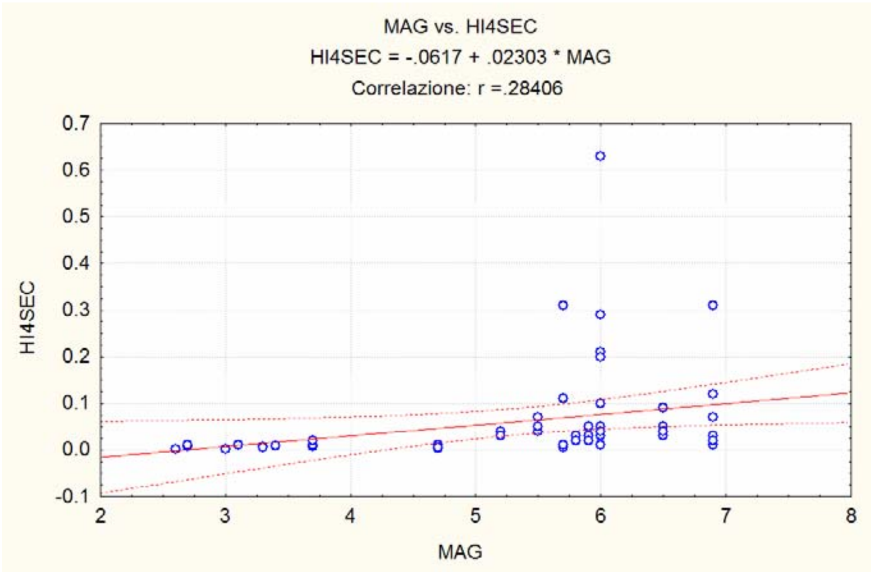

Figure 4: Earthquake magnitudo Vs. HI of the first 4 sec of the P_wave calculated by Sa_SEW

The estimated PGA is obtained using the site PGA regression low. Also interesting is the relation between the magnitudo and the Modified Housner Integral HI. This gives the element to evaluate the available Warning Time for the relevant Strategic infrastructures and CUHES in Italy. A dedicated net of SA_SEW sensors nested within the Italian seismological network stations held by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) is shown in fig. 5 to alert the relevant strategic infrastructures.

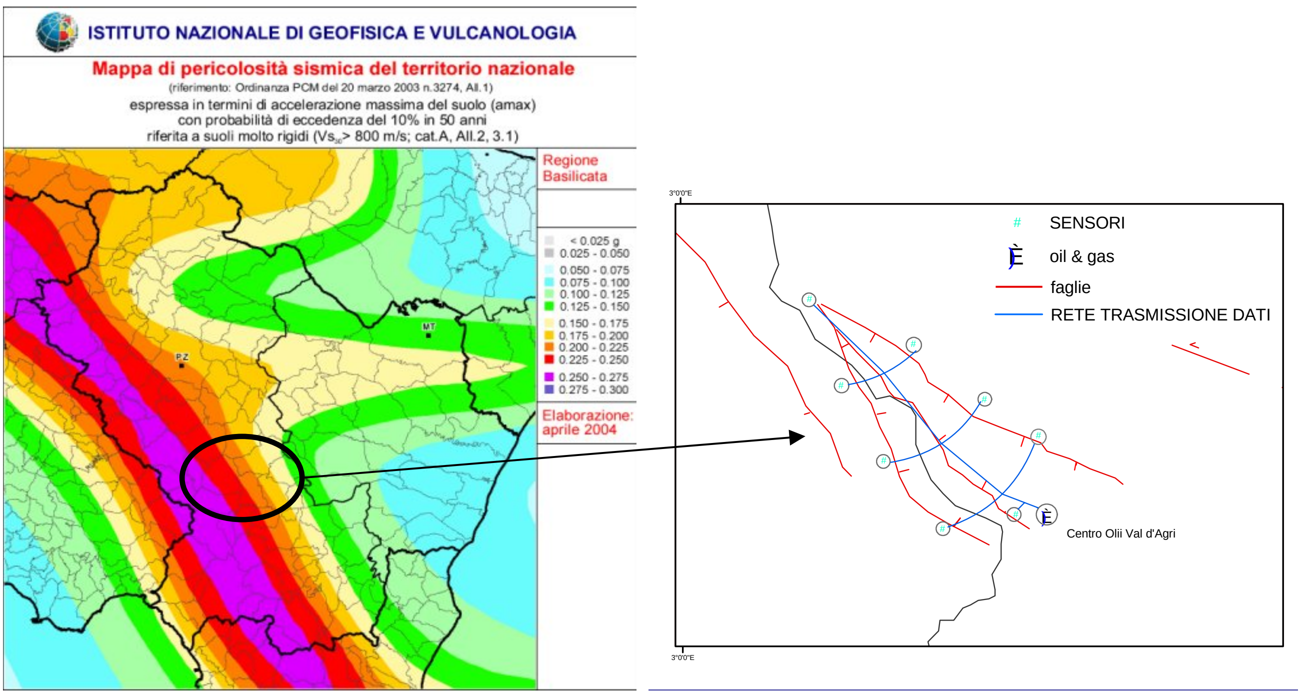

Figure 5: Dedicated SA_SEW sensors nested within the AMRA-INGV Italian seismic alert network.

The multi-sensor system has a computational grid structure; each sensor network has its specific ability to acquire and pre-analyze data which will then be sent to the Control Centre. The Sensor sub network encompass the following functions:

(a) environmental data acquisition, such as:

- soil analysis, by using instruments typical of earthquakes prediction
- satellite data (i.e. SAR
- interaction with weather forecast predictions
- Anti-flood sensors (level of natural waters -rivers, sea,)
- fire sensors (also satellite patrol)

(b) infrastructures data, such as
- control of the integrity for status of CUHES
- Sensors controlling other infrastructures strongly interdependent to the main infrastructure under control, such as the museum building.

The DSS can be hierarchically accessed by the different players involved in the control, from Civil Protection, to Regional and Local operators for Security, to Infrastructure's owners and managers, through the definition of a multiple-users sw environment, based on both client-server and web technologies.

3. ROCKING RESPONSE OF STATUES AND SHAKING TABLE TESTS

The dynamic response of statues to earthquakes, in analogy with free-standing blocks, is strongly non linear and depends essentially on the slenderness α, the frequency parameter P and the spectral shape and intensity of the ground acceleration time history. Those parameters define the possible act of motion of the statue: ground rigid, slide or rocking

$$\alpha = \arctan(X / Z) \qquad (2)$$

$$P = \sqrt{W \cdot R / I_o} \qquad (3)$$

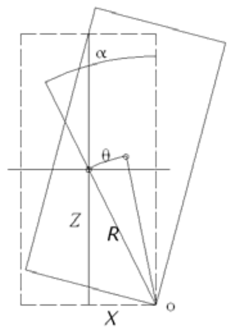

Figure 6. Dynamics of free standing block rocking pivoting about the edge O.

A parametric study of the dynamic response of statues with different values of slenderness α and frequency P with different earthquakes defines a series of Rocking Spectra to estimate their rocking dynamics. This procedure is in accordance with the U.S. Federal Emergency Management Agency Guidelines "FEMA356 (2000)".
On the other end, alternative approaches based on the Response Spectra of oscillating pendulum can be used through numerical integration of the (non linear) equation of the rocking motion. In presence of horizontal ground acceleration the dependency from α and P of the dynamic equation governing the rocking motion is:

$$\ddot{\theta}(t) + p^2 \sin(sig(\theta) \cdot \alpha - \theta(t)) = \frac{\ddot{u}(t)}{g} \cos(sig(\theta) \cdot \alpha - \theta(t)) \qquad (4)$$

Where $\ddot{u}(t)$ and g are the horizontal and gravity acceleration "Housner (1963) ". An extensive shaking table experimental campaign at the ENEA Research Centre of Casaccia, Roma, Italy is in course to verify the dynamics of statues protected by the "Earlyprot" devices and to validate the different design methodologies for free standing rigid blocks. Different order of problems must be solved in the shaking table experimental campaign to verify the protection system. First of all the minimum horizontal acceleration activating the rocking phase of the statue, secondly the horizontal impulse activating the instability of the statue (.e.g. the minimum collapse acceleration).The test scheme of the shaking table experiment for the seismic protection of relevant Cultural

Heritage Structures (e.g. statues like the David of Michelangelo) using very low damping passive seismic isolators and protecting cage with airbags, locked in normal condition and activated by a SEW triggered signal is shown in figure 7.

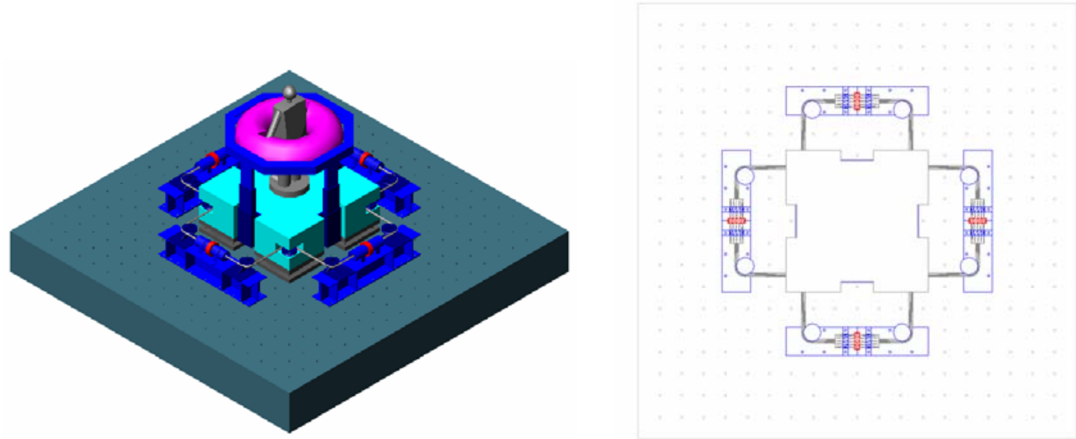

Figure 7: Lay out of the shaking table experiment

The cage with airbags, hidden in the basement, is activated by the SEW signal. The airbags function is to hold the statue during the earthquake, they skim the statue and the inflation is not explosive to avoid shocks. The design of a seismic isolated basement for the shaking table experiments with Very Low (almost zero) Damping Ceramic Spherical Pendulum (VLDCSP) seismic isolators, locked in normal condition and activated by the SEW signal, is shown in figure 8

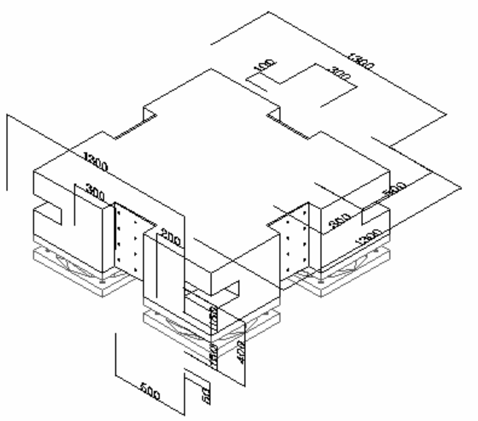

Figure 8: design of a seismic isolated basement for the shaking table experiments with Very Low (almost zero) Damping Ceramic Spherical Pendulum (VLDCSP) seismic isolators

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