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Non linear vertical-rocking isolation system: Application to legged wine storage tanks

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A B S T R A C T

In the last 30 years, there has been a great development of seismic isolation systems. The most used are elastomeric type devices and frictional pendulum bearings. Although different, both types generate horizontal seismic isolation, but not vertical. This study presents a nonlinear three-dimensional seismic isolation system called vertical rocking isolation (VRI) system, based on devices called ISO3D. Unlike conventional seismic isolators, the ISO3D device is vertically flexible and laterally stiff. Although the proposed system can be applied to any type of structure, it is particularly attractive as a seismic protection system of special structures, such as fluid storage tanks supported on legs, power transformers and sensitive equipment with vertical acceleration. In this research an application to legged wine storage tanks is presented. Two models were studied: a 3 m^3 tank with 4 legs, and a 30 m^3 tank with 6 legs. The fluid-structure interaction was considered using a quasi-static approach, where the fluid behaves as a mass attached to the tank walls. Time-history analyses results show average reductions of axial loads and shear loads on the legs of 57% and 61%, respectively. Finally, a fragility analysis indicates that the PGA required to reach 50% of probability of failure increases by an average of 153% by using the VRI system.

1. Introduction

During last 30 years there has been a great development of seismic isolation systems. The most used are elastomeric type devices, with and without a lead core, and frictional pendulum bearings, with single and double curvature. Although different, both devices generate horizontal seismic isolation, i.e. three lateral-torsional low frequency modes, but not vertical.

A three-dimensional seismic isolation system called GERB-BCS (Base Control System), which consists of a set of helical compression springs and viscous dampers on which the structure rests is available. With the use of these devices, the structure can be seismically isolated both horizontally and vertically. The principle of operation is identical to the well-known concept of vibration isolation in industrial equipment, i.e. six low frequency modes: three lateral-torsional modes, and three vertical-rocking modes.

The aforementioned systems can be used for any type of structure (buildings, industrial facilities, or equipment). Several authors have proposed seismic isolation systems designed for specific applications. For example, for fluid storage, the following can be mentioned: Shrimali and Jangrid [1], Cho et al. [2], Panchal and Jangid [3,4], Abali and Uckan [5], Shekari et al. [6]; and Soni et al. [7]. In order to seismically protect light structures such as legged wine storage tanks, the Rubber-Layer Rolling Bearing (RLRB) device [8,9] can be used. This kind of base isolation device, apart from reducing the lateral seismic loads, could reduce the axial loads and avoid leg buckling. Another way to seismically protect structures is through the use of energy dissipators. A novel system of dissipation that allows to reduce the vertical loads is described by Foti et al. [10].

The seismic behavior of storage structures has been studied extensively. For silos containing grain-like material, the following studies can be mentioned: Silvetry et al. [11,12]. For fluid storage, stainless steel tanks (SST) are commonly used. This type of structure is probably one of the most vulnerable to earthquake damage. The use of SST for fermentation and wine storage began in the 1950s in USA [13], and approximately three decades later in Chile and Argentina. The main advantages of SST over tanks made of other materials are: (i) ease of cleaning; (ii) relative chemical inertness; (iii) improved control of the fermentation process; and (iv) their aesthetic appeal. Thus, reinforced concrete tanks have been replaced almost completely by SST. Nevertheless, the first generation of SST was not designed considering earthquake resistant criteria. The ease of construction and use of a minimal amount of material were probably the prevailing criteria in early designs

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Nomenclature

α	angle of inclination of damper wedge
β	isolator slenderness as a function of vertical deformation, $b(u)/H_o$
β_o	isolator initial slenderness, b_o/H_o
$\ddot{d}_{gx}$	ground acceleration in the X-direction
$\ddot{d}_{gy}$	ground acceleration in the Y-direction
Γ_1	surface with null relative pressure
Γ_2	contact surface between fluid and structure
$\hat{\omega}$	frequency of the vertical deformation to calculate equivalent stiffness
$\hat{f}_o$	dimensionless expression for f_o
$\hat{f}_u$	dimensionless expression for f_u
$\hat{k}_u$	dimensionless expression for k_u
$\hat{u}$	dimensionless expression for $u, u/H_o$
PGA_h	horizontal peak ground acceleration
μ	steel on steel friction coefficient
Ω	volumetric domain
ω_z	vertical low frequency
$\omega_{\theta x}$	rocking around the X-axis low frequency
$\omega_{\theta y}$	rocking around the Y-axis low frequency
Ω_x	dimensionless relationship between vertical stiffness and mass distribution, ρ_{sx}/ρ_{mx}
Ω_y	dimensionless relationship between vertical stiffness and mass distribution, ρ_{sy}/ρ_{my}
ϕ	steel on steel friction angle
ρ	wine density
ρ_{mx}	mass radii of gyration with respect to the X-axis
ρ_{my}	mass radii of gyration with respect to the Y-axis
ρ_{sx}	stiffness radii of gyration with respect to the X-axis
ρ_{sy}	stiffness radii of gyration with respect to the Y-axis
$\ddot{\boldsymbol{d}}_g$	ground acceleration vector
$\ddot{\boldsymbol{q}}_a$	absolute fluid acceleration
$\hat{\boldsymbol{n}}$	vector in normal direction to tank surface
$\boldsymbol{C}$	structure viscous damping matrix
$\boldsymbol{F_u}$	vector of non-linear vertical forces
$\boldsymbol{K}$	structure stiffness matrix
$\boldsymbol{L_f}$	kinematic transformation matrix of non-linear vertical forces
$\boldsymbol{M_f}$	attached fluid mass matrix
$\boldsymbol{M}$	structure mass matrix
$\boldsymbol{N_p}$	matrix of the shape functions corresponding to the hydrodynamic pressure
$\boldsymbol{N_q}$	matrix of the shape functions corresponding to the displacement field of the structure
$\boldsymbol{P}(t)$	nodal hydrodynamic pressure
$\boldsymbol{q}(t)$	nodal displacement of the structure
$\boldsymbol{R}$	structure incidence matrix
$\boldsymbol{S}$	fluid-structure interaction matrix
ξ	damping ratio
$b(u)$	isolator opening as a function of vertical deformation
b_o	isolator initial opening
b_p	damper plates width
C	spring index, D/d
c	velocity of the compression wave in wine
D	spring mean diameter
d	spring wire diameter
E	elastic modulus of the steel
e_p	damper plates thickness
f	isolator non linear vertical force
f_o	spring pre-stressing load
f_s	spring load
f_u	isolator vertical elastic force
f_μ	damper vertical force
H_o	isolator initial height
h_p	damper plates height
I	damper plates flexural moment of inertia
K_b	modulus of volumetric compressibility
k_p	lateral stiffness of dampers plates
k_s	spring stiffness
k_u	isolator vertical elastic stiffness
K_z	total equivalent vertical stiffness
k_{zj}	equivalent vertical stiffness of the j-th isolator
L	isolator axis distance
M	moment in torsion spring
m	mass of the structure, assuming rigid body
N	leg axial force
N_a	spring active coils or wave
P	force in extension or compression spring
p	hydrodynamic pressure
q	displacement of the structure
S	spring stress
s	spring deformation
t	wall tank thickness
u	isolator vertical deformation
$U(\cdot)$	heaviside function
u_h	half amplitude of the vertical deformation to calculate equivalent stiffness
u_o	damper gap length
V	leg total shear force
v	damper plates lateral deformation
V_r	leg radial shear force
V_t	leg tangential shear force

[13]. Consequently, destructive earthquakes put these early designs of SST to test, often with poor results. The seismic performance of wine tanks has been recorded several times: Caucete Earthquake [14,15], Greenville [16], Morgan Hill [17], Loma Prieta [18], San Simeon [19], and Lake Grassmere [20]. But the event that has certainly brought greater information has been the Maule Earthquake [21,22]. This earthquake affected almost all Chilean wineries. Losses amounted to approximately 125 million liters of wine, representing 12.5% of production in 2009. The earthquake struck a week before the beginning of the harvest, when only 50% of storage tanks were in use. This indicates that more than 25% of tanks with wine lost all or part of their content. Wine tanks can be classified in two groups: (a) flat base (or continuous support) tanks; and, (b) legged tanks. The first are used to store volumes between 30 m^3 and 400 m^3; while the latter are used for volumes between 2 m^3 and 50 m^3. Smaller, legged tanks store the best-quality wine, however, so their potential failure can cause major economic losses. The main components of the legged tanks, and typical failures observed during the Maule Earthquake are shown in Fig. 1.

This research presents a nonlinear three-dimensional seismic isolation system called vertical rocking isolation (VRI) system, which is based on devices called ISO3D. Unlike conventional seismic isolators, the ISO3D device is vertically flexible and laterally stiff. The seminal idea was proposed by Almazán et al. [23], where linear behavior of the devices was considered. Although this idea can be applied to any type of structure or industrial equipment [24], the results shown here are only for legged wine storage tanks. The critical element of this type of structure are the legs, because they are very sensitive to axial load increments. One way to control the increase of compression loads on the legs is by using the VRI system. In addition, high vertical accelerations, caused by large