SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

RE-CENTRING CAPABILITY OF FRICTION PENDULUM SYSTEM: PARAMETRIC INVESTIGATION

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ABSTRACT

Self-centring capability after the seismic shaking is one of the fundamental functions required to seismic isolation systems. Low re-centering capacity may lead to serious damage and even structural collapse due to excessive cumulative displacements. Near fault quakes, frequently characterized by large pulse, may have a strong impact on the behavior of the isolation systems leading in some cases, to instability phenomena.

In this paper are reported some preliminary results relevant to an extensive parametric study aimed to investigate the re-centering capability of Friction Pendulum System (FPS) isolators and its sensitivity to pulse-like ground motions. A wide range of devices and ground motions, characterized by different values of the isolator characteristic parameters (equivalent radius R_{eq} and coefficient of friction μ_{eq}) and of the pulse-like characteristics of the seismic ground motion has been considered. The latters have been calculated in terms of the "predominant period" of the ground motion and through the introduction of a "kinetic Pulse Index" defined in terms of the rate of transmission of the kinetic energy.

The preliminary results, discussed herein in terms of maximum and residual displacements of the isolators, show that both the mechanical properties of the isolator (restoring stiffness and frictional damping) and the characteristics of the ground motion, but also their relationships, may have an important influence on the recentering capability of the devices.

INTRODUCTION

Re-centering related to a seismic isolation device represents the capability of the same to recover its original configuration after a seismic event. The parameter used to quantify this aspect is the residual displacement of the device at the end of the seismic shaking (often measured as a percentage of the maximum one). Re-centering capability must be carefully taken into account particularly for devices with low restoring forces since, in certain cases, the lack of recentering capability may lead to serious damages and even structural collapse due to excessive cumulative displacements. The evaluation of the

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re-centering capability of isolated structures is a controversial matter as witnessed by the fact that current standards, AASHTO (2010), EN1998-2 (2005), and EN 15129 (2009), do not provide homogenous readings (Cardone, 2012 and Medeot, 2013).

According to Katsaras (2008) the response of a hysteretic isolation system (both rubber and sliding isolators) in terms of restoring capability may be subdivided into two stages: the first one is the *strong-motion stage*, in which the system absorbs energy from the seismic shaking, and the second one is the *coda stage*, in which seismic energy input is insignificant with respect to that dissipated by the isolation system. Furthermore the coda stage is mainly governed by the isolator properties whereas the strong-motion stage is also strongly affected by ground motion details. Several seismologists have suggested that base-isolated buildings are vulnerable to large pulse-like ground motions generated at near-fault locations (Heaton *et al.*, 1995, Hall *et al.*, 1995). Such ground motions are characterized by a clear predominant period, one or more displacement pulses with peak velocities up to 1 m/s, and durations of few seconds. These pulses have a large impact on the isolation systems with natural periods in the same range since they usually produce large displacements which, especially for elastomeric bearings, may cause instability. In this regard a proposal of an optimal design of both elastomeric and sliding isolators was first formulated by Jangid *et al.* (2005 and 2007).

Some recent numerical studies (Katsaras, 2008, and Cardone, 2012) have shown that the main parameter influencing the restoring capability of the isolation system is the ratio d_{max}/d_{rm}, where d_{max} is the maximum seismic displacement and d_{rm} is the maximum residual displacement under which the system can be in static equilibrium (see the following section). It must be noted that the maximum earthquake displacement d_{max} includes the effect of the excitation, whereas d_{rm} is a characteristic parameter of the isolation system. It was shown that, for a given system, the re-centring capability is higher for ground motions inducing larger displacements.

Dicleli *et al.* (2005) studied the combined effect of isolator, ground motion, and substructure characteristics on the performance of seismic-isolated bridges. In particular it was found that the response of this kind of structures strongly depends on the ratio between the peak ground acceleration and the peak ground velocity (a_{peak}/v_{peak}) of the earthquake.

In this paper some preliminary results of a parametric study on the re-centering capability of friction pendulum seismic isolation devices are reported. The sensitivity of the re-centering capability to both the characteristics of the device and the features of the ground motion has been investigated through non-linear dynamic analysis of a single degree of freedom system. A large set of real earthquakes selected has been selected basing on their content of strong velocity pulse and a number of isolation devices has been modelled by varying the parameters of the model in order to include a large range of isolator prototypes.

THE FRICTION PENDULUM SYSTEM

The Friction Pendulum System (FPS), also known as Curved Surface Slider (CSS), is today a well-established anti-seismic hardware for base isolation of buildings and structures. Among the main advantages offered by CSS isolators are the compact design and smaller dimensions with respect to seismic rubber isolators with equal load and displacement capacity, the period of vibration independent on the mass of the isolated superstructure, and the absence of torsional effects for asymmetric buildings.

The principal elements of an FPS device are two or more concave steel sliding surfaces in contact through friction pads of self-lubricant material. The principles of operation of the Friction Pendulum is the same of a typical pendulum: the relative motion along the steel sliding surfaces lengthens the natural period of the structure decreasing the seismic forces transmitted to the structure itself. The combined effects of the curvature of the sliding surfaces and of the weight of the superstructure provides a certain re-centering capability and the seismic energy is dissipated by means of frictional forces at the sliding interfaces. The dissipating capacity depends on the characteristics of the material used for the friction pads. The typical hysteretic loop of the CSS isolator is represented in Fig.1. The undamped natural period of vibration T_{is}, the effective period $T_{is,eff}$, the characteristic strength Q and the stiffness k_2 can be determined through the following equations:

$$T_{is} = 2\pi\sqrt{R_{eq}/g} \tag{1}$$

$$T_{is,eff} = 2\pi\sqrt{R_{eq}/g\left(1+\mu_{eq}R_{eq}/d_{\max}\right)} \tag{2}$$

$$Q = \mu_{eq} \cdot N \tag{3}$$

$$k_2 = N/R_{eq} \tag{4}$$

where N is the weight of the supported structure, d_{max} is the amplitude of the cycle, R_{eq} and μ_{eq} are respectively the equivalent radius and the friction coefficient of the curved surfaces (Zayas *et al.* 1987, 1990).

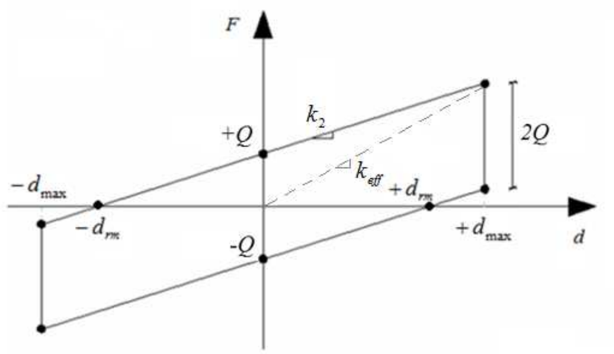

Figure 1. Typical hysteretic loop of a friction pendulum isolator

During severe earthquakes, devices with low stiffness k_2 may undergo significant displacements and may exhibit inadequate recentering capability particularly in the case that high friction materials are used for the pads. In this regard the maximum static residual displacement d_{rm}, defined as the residual displacement attained when the system is unloaded under quasi-static conditions from its design capacity d_{max}, can be calculated as follows: $d_{rm} = \mu_{eq} \cdot R_{eq}$.

The acceleration threshold over which a seismic event activates the device, that is the sliding along the curved surfaces occurs, is the critical acceleration $a_{cr} = g\mu_{eq}$.

CHARACTERISTICS OF THE GROUND MOTION

Several experimental and numerical studies (Dicleli, 2005, and Cardone, 2012) have shown the strong relationship between the re-centering behavior of seismic isolation devices and the content of strong velocity pulse in the input ground motion. Specifically earthquakes containing strong velocity pulse are likely to impose high demand in terms of displacements thus affecting the re-centering after a strong ground shaking. A ground motion is classified as “pulse-like” if the velocity time-history contains a pulse which is a large portion of the ground motion (Baker 2007). A quantitative criterion for the identification of “pulse-like” quakes, based on signal processing through wavelet analysis, was first proposed by Baker in 2007 and later enhanced by Shahi *et al.* in 2011. The Baker’s approach is based on the quantification of the relative importance of the largest velocity pulse extracted from the ground motion with respect to the remaining part of the signal.

In this paper a different approach is adopted, based on the rate of transmission of the kinetic energy to the structure. Specifically a kinetic pulse index PI_k is defined in terms of the ratio between the time interval $D_{v,T}$ across which a significant amount of kinetic energy is transmitted to the structure with respect to the significant duration of the quake $D_{v,B}$:

$$PI_k = 1 - \frac{D_{v,T}}{D_{v,B}} \quad (5)$$

being $D_{v,T}$ and $D_{v,B}$ respectively the Trifunac (Trifunac *et al.*, 1975) and bracketed (Bolt, 1969) durations of the ground motion, both calculated in terms of velocities.
The higher PI_k, the shorter the time interval of transmission of the kinetic energy.
The Trifunac duration $D_{v,T} = t_{0.95 I_E} - t_{0.05 I_E}$ in terms of velocity is calculated as the time interval between 5% and 95% of the energy integral I_E (Anderson, 2004):

$$I_E = \int_0^{\infty} v_g^2 dt \quad (6)$$

The bracketed duration $D_{v,B}$ is the total time between the first and the last exceeding of a given threshold during the strong motion. Herein the threshold has been fixed at 1% of the absolute peak velocity.

The basic idea behind this approach for the detection of "pulse-like" earthquakes is that the shorter the time interval during which a significant amount of kinetic energy is transmitted to the structure, the higher the demand imposed to the structure in terms of peak velocity. Moreover, also the predominant period of the pulse T_p can have a strong effect on the structural response depending on its relationship with the effective period of the structure. Herein the value of T_p has been estimated as the period T_{sv} corresponding to the peak of the undamped ground motion velocity response spectrum.

PARAMETRIC STUDY

The re-centring capability of friction pendulum isolators was investigated by means of an extensive parametric study in terms of the values of the maximum d_{max} and residual d_{res} displacement under a given earthquake. The variables considered in the investigation were both the governing properties of the devices (equivalent coefficient of friction μ_{eq} and radius R_{eq}) and the characteristics of the ground motion (pulse index PI_k and fundamental period T_{sv}).

A wide range of devices were taken into account: twelve isolator prototypes were defined varying both equivalent radius R_{eq} and the friction coefficient μ_{eq} over typical ranges for the design of seismically isolated structures (respectively 1.0m-4.0m and 0.02-0.15). A vertical load N equal to 80.4kN was assumed to model the weight of the superstructure. Table.1 reports the values considered for the two parameters together with the corresponding values of stiffness k_2, of the maximum static residual displacement d_{rm} and of the undamped period of the device T_{is}.

Table 1. Characteristic parameters of the considered curved surface slider prototypes

Prototypes	R_{eq} [m]	μ_{eq} [-]	T_{is} [sec]	k_2 [kN/m]
FPS 1.1	1.00	0.02	2.00	80.4
FPS 1.2	1.00	0.06	2.00	80.4
FPS 1.3	1.00	0.10	2.00	80.4
FPS 1.4	1.00	0.15	2.00	80.4
FPS 2.1	2.20	0.02	2.97	36.5
FPS 2.2	2.20	0.06	2.97	36.5
FPS 2.3	2.20	0.10	2.97	36.5
FPS 2.4	2.20	0.15	2.97	36.5
FPS 3.1	4.00	0.02	4.01	20.1
FPS 3.2	4.00	0.06	4.01	20.1
FPS 3.3	4.00	0.10	4.01	20.1
FPS 3.4	4.00	0.15	4.01	20.1

In order to ensure a great variety of possible seismic scenarios, a large number of unscaled records were downloaded from the Pacific Earthquake Engineering Research Center (PEER) database and then subdivided into groups taking into account their "pulse-level" and fundamental period. In this regard four ranges of the predominant period T_{sv} were established covering the whole range of periods of the prototypes previously defined:

(1) $T_{sv} \leq 2.0$ sec;

(2) $2.0 < T_{sv} \leq 3.0$ sec;

(3) $3.0 < T_{sv} \leq 4.0$ sec;

(4) $T_{sv} > 4.0$ sec.

Moreover, basing on the values of PI_k and on the comparison with the classification proposed by Baker (2007) for “pulse” and “no pulse” earthquakes, three ranges were defined to distinguish between earthquakes corresponding to a different content of a dominant strong velocity pulse:

(1) no-pulse $PI_k < 0.40$;

(2) weakly pulse $0.40 \leq PI_k \leq 0.70$;

(3) pulse $PI_k > 0.70$.

Thirty-six recorded records were selected and subdivided in twelve homogeneous groups according to the ranges previously defined (Table.2).

Table 2. Characteristic parameters of the selected records

T_{sv} range [sec]	Type	PEER ID	Event description	T_{sv} [sec]	PI [-]
T_{sv} < 2 sec	no pulse	nga_no_59_csm185	San Fernando, 1971	0.56	0.09
		nga_no_303_b-stu000	Irpinia eq, 1980	0.22	0.15
		nga_no_49_sad003	Lytle Creek, 1970	0.18	0.15
	weakly pulse	nga_no_460_gmr090	Morgan Hill, 1984	0.34	0.50
		nga_no_496_s2330	Nahanni, 1985	0.57	0.56
		nga_no_156_f-csc-ns	Norcia eq, 1979	0.38	0.52
	pulse	nga_no_451_cyc285	Morgan Hill, 1984	0.78	0.86
		nga_no_150_g06230	Coyote lake, 1979	1.09	0.89
		nga_no_766_g02090	Loma Prieta, 1989	1.47	0.84
2 < T_{sv} < 3 sec	no pulse	nga_no_82_phn180	San Fernando, 1971	2.34	0.23
		nga_no_453_fre345	Morgan Hill, 1984	2.40	0.29
		nga_no_2108_0528360	Alaska, 2002	2.18	0.29
	weakly pulse	nga_no_827_for000	Cape Mendocino, 1992	2.92	0.51
		nga_no_833_wba000	Landers, 1992	2.34	0.48
		nga_no_247_l-bpl070	Mammoth Lakes, 1980	2.54	0.60
	pulse	nga_no_292_a-stu270	Irpinia eq, 1980	2.34	0.82
		nga_no_171_h-emo270	Imperial Valley, 1979	2.67	0.85
		nga_no_802_stg090	Loma Prieta, 1989	2.82	0.75
3 < T_{sv} < 4 sec	no pulse	nga_no_2102_1397090	Alaska, 2002	3.14	0.25
		nga_no_51_pve155	San Fernando, 1971	3.72	0.20
		nga_no_297_b-bis270	Irpinia eq, 1980	3.73	0.39
	weakly pulse	nga_no_1167_kut090	Kocaeli, 1999	3.18	0.52
		nga_no_827_for090	Cape Mendocino, 1992	3.06	0.46
		nga_no_1156_cnk180	kocaeli, 1999	3.28	0.52
	pulse	nga_no_181_h-e06230	Imperial Valley, 1979	3.08	0.89
		nga_no_185_h-hvp315	Imperial Valley, 1979	3.39	0.71
		nga_no_182_h-e07230	Kocaeli, 1999	3.66	0.85
T_{sv} > 4 sec	no pulse	nga_no_834_arc262	Landers, 1992	4.40	0.35
		nga_no_2100_k205090	Alaska, 2002	5.41	0.35
		nga_no_75_ma2130	San Fernando, 1971	5.79	0.20
	weakly pulse	nga_no_1170_mcd090	Kocaeli, 1999	4.68	0.59
		nga_no_1170_mcd--v	Kocaeli, 1999	5.36	0.59
		nga_no_2115_ps11066	Alaska, 2002	5.87	0.47
	pulse	nga_no_179_h-e04230	Imperial Valley, 1979	4.53	0.76
		nga_no_1148_arc090	Kocaeli, 1999	5.22	0.70
		nga_no_185_h-hvp225	Imperial Valley, 1979	4.23	0.69

All the records were scaled to the same value of the peak acceleration $a_{peak} = 4m/s^2$ selected to be higher than the maximum critical acceleration a_{cr} of the selected FPS isolators. The nonlinear dynamic analysis were conducted using the software NONLIN v.5.50 (Charney *et al.*, 2004). Assuming a rigid body behaviour of the superstructure, the friction pendulum isolators is modelled as an elastic-plastic SDOF system with an initial stiffness k_1, a secondary stiffness k_2, and the yield strength F_y (see Fig.2).

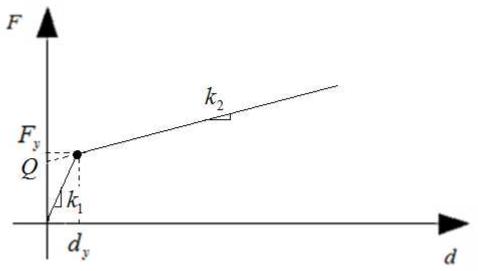

Figure 2. Initial and post-yielding stiffness model for numerical analysis

The characteristic strength Q and the secondary stiffness k_2 were calculated basing respectively on eq. (3) and (4); the yielding displacement d_y and the corresponding force F_y are given by:

$$d_y = \frac{Q}{k_1 - k_2} \tag{7}$$

$$F_y = k_1 d_y \tag{8}$$

The initial stiffness was fixed to k_1 =8000kN/m.

RESULTS

For each considered FPS prototype, thirty-six nonlinear analysis were performed by applying all the seismic input reported in Table.2. The displacements time histories were calculated in order to estimate the maximum d_{max} and residual d_{res} displacements at the end of the earthquake.

Fig.3 shows for the isolator FPS 1.4 (R_{eq}=1.00m, μ_{eq} =0.15) the differences between the displacement time histories and between the force-displacement loops relevant to ground motions with different values of the kinetic Pulse Index. Specifically the responses to a “no-pulse” (nga_no_2100_k205090), a “weakly-pulse” (nga_no_833_wba000), and a “pulse” (nga_no_1148_arc090) earthquakes are reported respectively in Fig.3 left, centre and right. In the last figure the presence of a pulse in the displacements time history is quite evident. Moreover it can be seen that oscillatory quakes ("no-pulse") are characterized by a sensibly higher number of hysteretic cycles with respect to weakly and “pulse-like” motions.

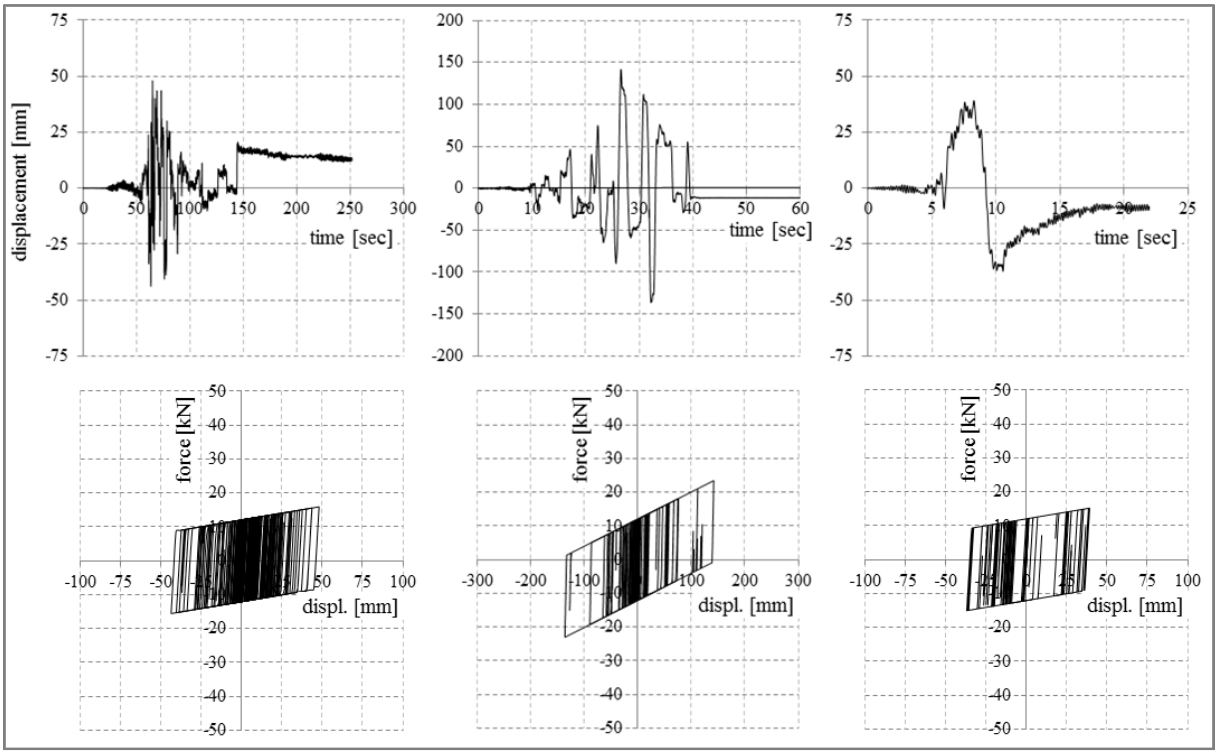

Figure 3. Displacement histories (up) and hysteretic loops (down) of prototype FPS 1.4 (R_{eq}=1.00m, μ_{eq} =0.15) subjected to “no-pulse” (left), “weakly-pulse” (centre), and “pulse” (right) quake

Fig.4 and 5 report the variation of respectively the maximum and residual displacements with the ratio T_{ratio} between the predominant period of the quake T_{sv} and the period of the device T_{is} given by eq.(1). The T_{ratio} was aimed to identify near-resonant conditions ideally corresponding to unit value of this parameter. Actually the effective period of the device, as shown by eq.(2), is lower than T_{is} hence near-resonant conditions actually occur for values of T_{ratio} higher than 1. This is clearly shown in Fig.4 (left) where the higher values of d_{max} occur for values of T_{ratio} in the range 1-3. The same near-resonant effect can be also observed for residual displacements at the end of the seismic shaking (Fig.4, right).

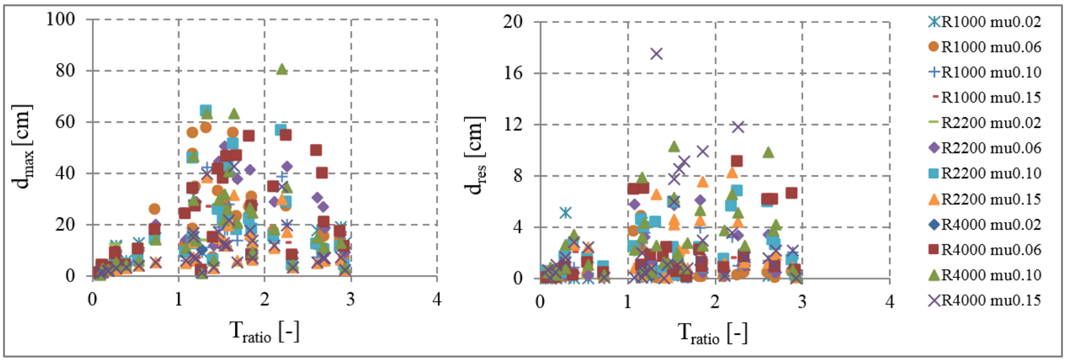

Figure 4. Near-resonance on the maximum (left) and residual (right) displacement

The sensitivity of the maximum and of the residual displacements to the equivalent radius R_{eq} has been investigated for different values of the equivalent friction coefficient $\mu_{eq.}$ and some results are shown in Fig.5. The maximum displacements appear scarcely affected by the secondary stiffness (function of R_{eq}) and exhibit a higher dispersion, with statistically higher values, for lower values of μ_{eq}.

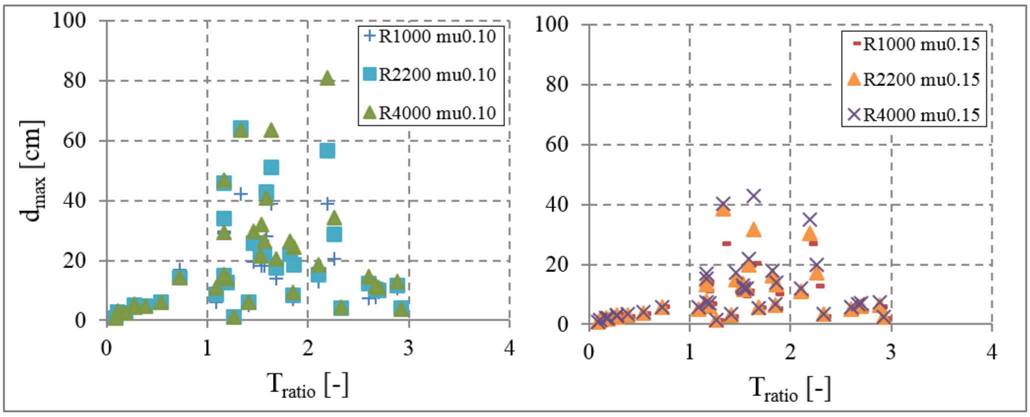

Figure 5. Comparison between the maximum displacements d_{max} of FPS isolators with μ_{eq} equal to 0.10 (left) and 0.15 (right)

On the contrary stiffer devices (lower values of R_{eq}) exhibit a better recentering capability as shown by Fig.6: at the decrease of R_{eq}, statistically lower values of the residual displacements are found. The dispersion of d_{res} tends to increase with the friction coefficient μ_{eq}.

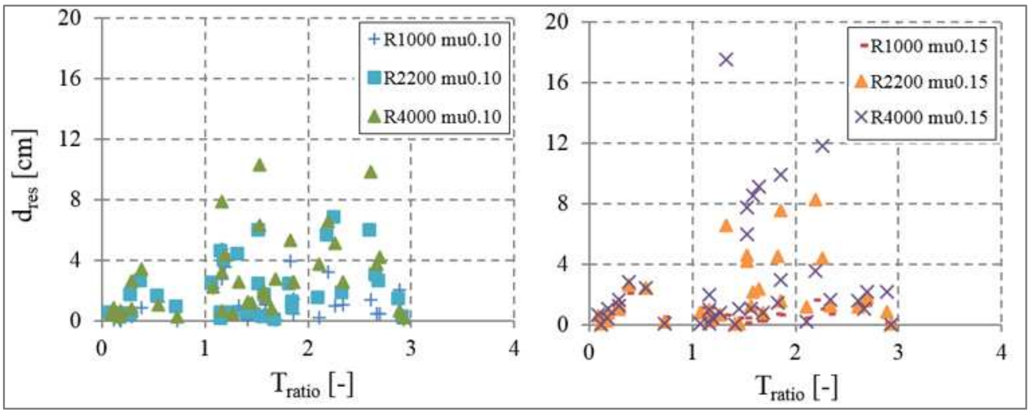

Figure 6. Comparison between the residual displacements d_{res} of FPS isolators with μ_{eq} equal to 0.10 (left) and 0.15 (right)

The sensitivity of the maximum and residual displacements to velocity pulses in the excitation was investigated in terms of the previously defined pulse index PI_k (eq.(5)) and some results are reported in Fig.7 and 8.

Each point in Fig.7 (d_{max}) and Fig.8 (d_{res}) corresponds to a single seismic event that is, for a given value of R_{eq} and PI_k, each point corresponds to a given T_{ratio}. For a certain value of the equivalent radius R_{eq}, both the maximum d_{max} and the residual displacements d_{res}, exhibit a very small dispersion when the index PI_k is lower than 0.5 while, beyond this value, the dispersion considerably increases. This indicates that the frequency content of no-pulse events (low values of PI_k) has a very limited effect on the magnitude of $d_{\max}$ and d_{res} while, on the contrary, for pulse events the maximum displacement sensibly depends on the T_{ratio} (hence on the predominant period of the quake, being T_{is} constant for a given R_{eq}).

Furthermore the envelope of the maximum displacements at the increase of PI_k approximately follows a linear trend within the range 0-0.5 approaching an asymptotic value beyond this value (Fig.7). This latter circumstance has not been deepened yet and will be the object of further investigations.

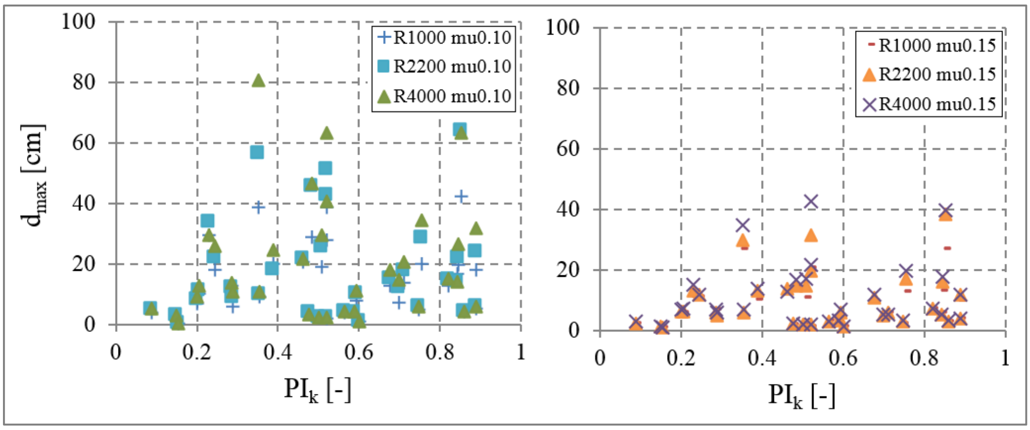

Figure 7. Maximum displacements d_{max} as a function of the pulse index PI_k: comparison between isolators with μ_{eq} equal to 0.10 (left) and 0.15 (right)

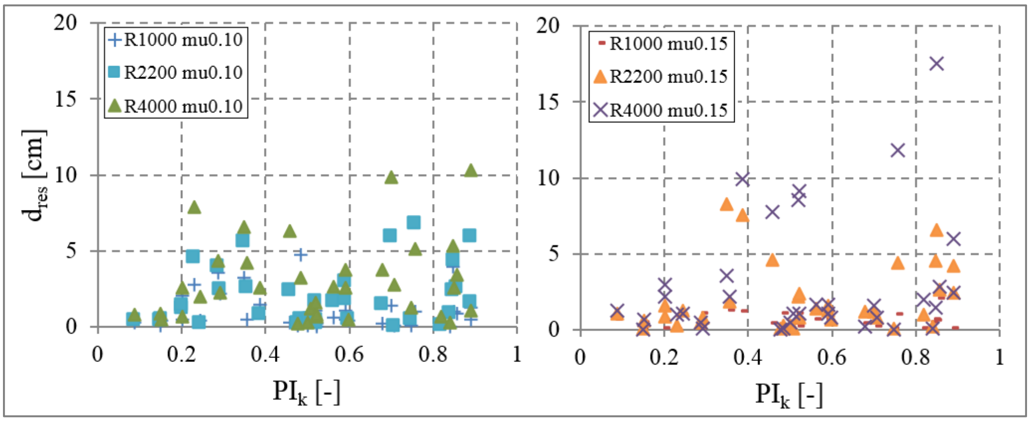

Figure 8. Residual displacements d_{max} as a function of the pulse index PI_k: comparison between isolators with μ_{eq} equal to 0.10 (left) and 0.15 (right)

CONCLUSIONS

In the present paper some preliminary results of a parametric study on the re-centering capability of FPS isolators are presented. The sensitivity of the maximum and the residual displacements induced by a seismic ground motion to the characteristic parameters of the device (characteristic strength Q and stiffness k_2) and to the features of the ground motion (predominant period T_p and "pulse-level" PI_k) was investigated.

Results show that:

- the maximum displacement decreases at the increase of the characteristic strength Q (that is of the coefficient of friction μ_{eq}) and of the stiffness k_2;
- the residual displacement increases with the characteristic strength Q and decreases with the stiffness k_2;
- both maximum and residual displacements significantly increase when the predominant period of the quake T_{sv}, approaches the effective period of the device;
- "pulse-like" waves are more likely to produce higher maximum d_{max} and residual d_{res} displacements with respect to "no pulse".

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