Earthquake and Structures Vol. 4, No. 3 (2013) 285-297
DOI: http://dx.doi.org/10.12989/eas.2013.4.3.285

Effect of soil-structure interaction for a building isolated with FPS

A. Krishnamoorthy*

Department of Civil Engineering, Manipal Institute of Technology, Manipal–576 104, Karnataka, India

(Received July 6, 2011, Revised October 10, 2011, Accepted June 9, 2012)

Abstract. The effect of soil structure interaction (SSI) on seismic response of a multi-degree-of-freedom structure isolated with a friction pendulum system (FPS) is studied. In the analysis, the soil is considered as an elastic continuum and is modeled using the finite element method. The effect of SSI on response of the structure is evaluated for twenty far-field and twenty near-fault earthquake ground motions. The effect of friction coefficient of sliding material of FPS on SSI is also studied. The results of the study show that the seismic response of the structure increases for majority of the earthquake ground motions due to SSI. The sliding displacement and base shear are underestimated if SSI effects are ignored in the seismic analysis of structures isolated with FPS.

Keywords: sliding bearing; friction pendulum system; soil-structure interaction; finite element method; far-field and near-fault ground motions

1. Introduction

The friction pendulum system (FPS) proposed by Zayas *et al*. (1990) is one of the most effective technique to control the response of the structure subjected to earthquakes. The sliding surface of FPS is spherical so that the gravitational force will provide a restoring stiffness that helps the structure to bring back to its original position at the end of an earthquake. Characteristics of the FPS pertaining to durability under severe environmental conditions, reduced height, and insensitivity to the frequency content of the ground motions, make it a viable option for seismic isolation (Eröz and DesRoches 2008). As a result, the system has now become popular and has found applications in both buildings and bridges. The structure resting on sliding surface will have two phases namely non-sliding phase and sliding phase. Because of the sliding and non-sliding phases exist alternatively; the dynamic behaviour of sliding structure is highly nonlinear. A simplest model, a rigid block sliding on a bed with two degrees of freedom, one for super-structure and the other for sliding foundation was proposed by Mostaghel and Tanbakuchi (1983) to model the response of a sliding structure. Yang *et al*. (1990) used a fictitious spring with a very large stiffness in the non-sliding phase and zero stiffness in the sliding phase to model the sliding bearing. Vafai *et al*. (2001) replaced a fictitious spring in the model of Yang *et al*. (1990) by a link

*Corresponding author, Ph.D., E-mail: akmoorthymit@gmail.com

with a rigid-perfectly plastic material. There have been significant investigations to study the effectiveness of FPS to isolate the structure subjected to earthquake ground motions.

However, in all these studies, the foundation of the structure is assumed as rigid and the flexibility of the supporting soil is neglected. It is well known that the actual behavior of structures not only depends on the stiffness of structure, but also on the stiffness of foundation and supporting soil system. Several investigations carried out to study the SSI effects on the response of a bridge isolated with rubber bearings (Chaudhary *et al.* 2001, Vlassis and Spyrakos 2001, Tongaonkar and Jangid 2003, Spyrakos and Loannidis 2003, Dicleli *et al.* 2005, Stehmeyer and Rizos 2008, Soneji and Jangid 2008, Ucak and Tsopelas 2008) showed that the SSI may either beneficial or detrimental to the response of isolated bridges. However, the above studies are limited to investigate the effects of SSI on the response of a bridge structure isolated with rubber bearing. To simplify the analysis, the nonlinear behavior of bearings is assumed as either linear or equivalent linear. In addition to simplify the analysis further, the foundation system in these studies is modeled using a simplified model consisting of a spring and dashpot. It may be noted that, under seismic excitation, the soil-structure interaction system is infinite and there exists energy exchange between superstructure and foundation (Takewaki 2005a, b). The analysis of FPS isolated structures is more complex compared to the analysis of linear rubber isolated structures due to the existence of sliding and non-sliding phases. The complexity of the analyses increases further when the effect of SSI is considered. Since this type of analysis is often complex and rare in the literature, this paper explains the procedure to model the FPS isolated multi-degree-of-freedom structure on soil using FEM and also discusses the effect of SSI on response of FPS isolated structure.

2. Analytical modeling

Fig. 1 shows the finite element modeling of the isolated structure, foundation and soil medium. In the finite element modeling, the structure is modeled as an assemblage of two noded plane frame element with two translational and one rotational degrees of freedom. The foundation beneath the sliding bearing and supporting soil mass are modeled as an assemblage of four noded plane strain element with two translational degrees of freedom (Takewaki 1998, Takewaki *et al.* 1998). The soil mass is assumed to be resting on the bed rock and there fore all the nodes at the base of the soil are taken as fixed. To simulate an infinite soil medium, Kelvin elements with spring and dashpot proposed by Novak and Mitwally (1988) are attached on the side walls of the soil mass. The sliding bearing between the base of the structure and foundation is modeled using a fictitious spring with one horizontal degree of freedom. The stiffness of the spring, k_s, is assigned a very high value (10^{15} kN/m) during non-sliding phase and its stiffness is equal to the stiffness of the isolator k_b during sliding phase. Seismic excitation is assumed to act at the fixed base nodes in horizontal direction. The overall dynamic equation of equilibrium for the structure-foundation-soil system can be expressed in matrix notation as

$$[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\} \tag{1}$$

where [*M*] is the mass matrix and [*K*] is the stiffness matrix. This matrix includes the stiffness of structure, foundation, soil medium, stiffness of springs at the boundary nodes, stiffness of the isolator, k_b, and stiffness of the fictitious spring, k_s. The damping of the system is assumed as

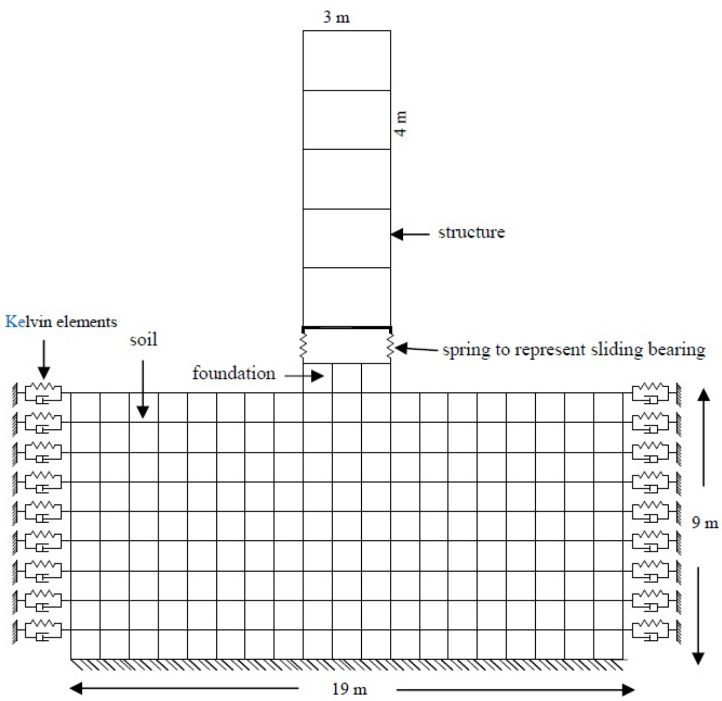

Fig. 1 Finite element discretization of structure-foundation-soil system

Rayleigh-type and the damping matrix $[C]$ is determined using the equation $[C] = \alpha[M] + \beta[K]$ where α and β are the Rayleigh constants. These constants can be determined if the damping ratios for both modes are known. Additional damping due to the radiation effects (dashpot) at the boundary nodes is added to the damping matrix of the soil at degrees of freedom corresponding to the boundary nodes. $\{\ddot{u}\}$, $\{\dot{u}\}$ and $\{u\}$ are the acceleration, velocity and displacement vectors relative to the ground (bedrock) at nodes and $\{F(t)\}$ is the nodal load vector. The nodal load vector is calculated using the equation

$$\{F(t)\} = -[M]\{I\}\ddot{u}_g(t) \tag{2}$$

$\{I\}$ is the influence vector and $\ddot{u}_g$(t) is the ground (bedrock) acceleration.

For a mass, m, sliding on a smooth curved surface, the restoring force, F_b, can be expressed as

$$F_b = m\omega_b^2 x \tag{3}$$

or

$$F_b = k_b x \tag{4}$$

ω_b is the isolator natural frequency and is equal to $\sqrt{g/R}$ (R is the radius of curvature of the isolator), x is the sliding displacement and k_b is the isolator stiffness equal to mg/R.

A structure resting on sliding type of support passes through two types of phases (1) a non-sliding phase and (2) a sliding phase. When the structure is resting on sliding type of bearing, the mobilized frictional force at the base of each column is equal to F_x. The maximum frictional resistance F_s offered by the sliding surface is equal to the product of the weight of the structure at the base of each column W and the friction coefficient μ (i.e., $F_s = \mu W$). It acts opposite to the direction of sliding. When the mobilized frictional force F_x at the base is less than the frictional resistance F_s (i.e., $|F_x| < F_s$), the structure will not have relative movement at the base and this phase of the structure is known as non-sliding phase. However, when the mobilized frictional force F_x is equal to or more than the frictional resistance F_s (i.e., $|F_x| \geq F_s$), then the structure starts sliding at the base and this phase of the structure is known as the sliding phase. When the structure is in the sliding phase and whenever reverses its direction of motion (when the relative velocity between the foundation and the superstructure at the base is equal to zero), then the structure at the base and foundation may move together and may enter the non-sliding phase or may slide in opposite direction.

3. Numerical examples

An example five-story plane frame structure as shown in Fig. 1 is considered to study the SSI effects on the response of a structure isolated with FPS. The radius of curvature of FPS is 1.0 m corresponding to the isolator natural period of 2.0 sec. The effect of SSI is studied for the friction coefficient of sliding material equal to 0.02, 0.05 and 0.1. These values may be considered as the low, medium and high and are in the range adopted in practice for FPS. The effect of SSI is studied for the structure supported on hard, medium and soft soils. The geometric and material properties of the super-structure, foundation and supporting soil are as follows

Super-structure:

Modulus of elasticity	$= 2.2 \times 10^7$ kN/m^2
Mass on each beam	$= 5.0$ kNsec^2 /m^2
Damping ratio	= 5%
Beam size	= 0.45 m × 0.45 m
Column size	= 0.45 m × 0.60 m

Foundation:

Modulus of elasticity	$= 2.2 \times 10^7$ kN/m^2
Mass density	$= 2.4$ kNsec^2 /m^4
Poisson's ratio	= 0.15
Damping ratio	= 5%

Soil:

Modulus of elasticity of soft soil	= 5000 kN/m^2
Modulus of elasticity of medium soil	= 50000 kN/m^2
Modulus of elasticity of hard soil	= 500000 kN/m^2
Poisson's ratio	= 0.33
Damping ratio	= 5 %
Mass density	$= 2.0$ kNsec^2 /m^4

It has been reported (Takewaki 2005a) that the damping ratio of the soil affects the response of the structure supported on soil mass. For the present study a damping ratio of 5% as listed above is considered. Similar damping ratio of 5% has been suggested by Vlassis and Spyrakos (2001) in

Table 1 Details of NF and FF set of earthquake ground motions

NF set of earthquake ground motions				FF set of earthquake ground motions			
Ground motion	ID	Station	PGA (m/s^2)	Ground motion	ID	Station	PGA (m/s^2)
Northridge	1	Olive view 1	8.243	Landers	1	Joshua 1	2.770
	2	Olive view 2	5.929		2	Joshua 2	2.687
	3	Rinaldi 1	8.359		3	Yermo 1	2.403
	4	Rinaldi 2	7.877		4	Yermo 2	1.481
Landers	5	Lucerne 1	8.028	Loma Prieta	5	Gilroy 1	3.531
	6	Lucerne 2	7.651		6	Gilroy 2	3.130
Kobe	7	Takatori 1	5.984		7	Hollister 1	2.673
	8	Takatori 2	5.915		8	Hollister 2	2.608
	9	Kobe 1	3.727	Northridge	9	Century 1	2.507
	10	Kobe 2	2.962		10	Century 2	2.173
Erzincan	11	Erzincan 1	4.927		11	Moorpark 1	2.854
	12	Erzincan 2	4.699		12	Moorpark 2	1.873
Cape Medocino	13	Petrolia 1	6.498	San Fernando	13	241-1	1.675
	14	Petrolia 2	5.784		14	241-2	2.521
Tabas	15	Tabas 1	8.355		15	438-1	1.060
	16	Tabas 2	8.199		16	438-2	1.103
	17	Tabas 3	6.749	El-Centro	17	El-Centro	2.844
Loma Prieta	18	Lex Dam	3.981	Irpinia	18		1.736
Chi-Chi	19	TCU075	2.965	Duzce	19		8.060
Gazli	20	Karokyr	7.357	Imperial Valley	20	El-Centro	2.990

order to realistically simulate moderately strong ground motions. Soneji and Jangid (2008) considered the damping ratio varying from 4% to 7% for different layers of medium and soft soils.

Maheshwari *et al.* (2005) proposed a similar damping ratio of 5% for the soil. The fundamental natural period of the structure fixed at the base (non isolated) is equal to 0.5 sec where as for the structure on soft, medium and hard soils it is equal to 1.38 sec, 0.6 sec and 0.49 sec respectively. It may be noted that the fundamental natural period of the structure on hard soil is similar to that of the fixed base structure whereas the fundamental natural periods of the structure on soft and medium soils is larger than that of the fixed base structure.

Twenty near fault and twenty far field real earthquake ground motions tabulated in Table 1 are considered to study the effect of SSI on isolated structure. The first set of twenty NF set of earthquake ground motions is with the magnitude larger than 6.5 and the epicentral distance between 10 and 20 km. The second set of twenty FF set of earthquake ground motions is with the magnitudes ranging from 6.7–7.4 and the epicentral distance between 0 and 10 km. Similar earthquake ground motions have been considered by Ucak and Tsopelas (2008) to investigate the effect of SSI on the response of a bridge isolated with rubber bearings. The structure is subjected to these forty earthquake ground motions and the sliding displacement and base shear response are obtained. The base shear is directly proportional to the forces exerted on the structure due to the earthquake ground motion. On the other hand, the sliding displacement of the super-structure is crucial from the design point of view of the isolation system and the expansion joints. The peak response of the isolated structure with SSI is normalized with respect to the peak response of the isolated structure fixed at the base (without SSI). The normalized base shear and sliding displacement are termed here as the base shear ratio (BSR) and sliding displacement ratio (SDR).

4. Effect of SSI for the structure subjected to NF and FF set of ground motions

The base shear and sliding displacement response obtained from the analysis for the isolated structure on soft, medium and hard soils subjected to twenty NF and twenty FF earthquake ground motions is tabulated in Tables 2-5. The effect of SSI on SDR and BSR values for soft, medium and hard soils is compared in Figs. 2-5. It can be observed from these figures and tables that the sliding displacement and base shear response of the structure on soft and medium soil are affected considerably due to SSI. For majority of the earthquakes, the sliding displacement and base shear

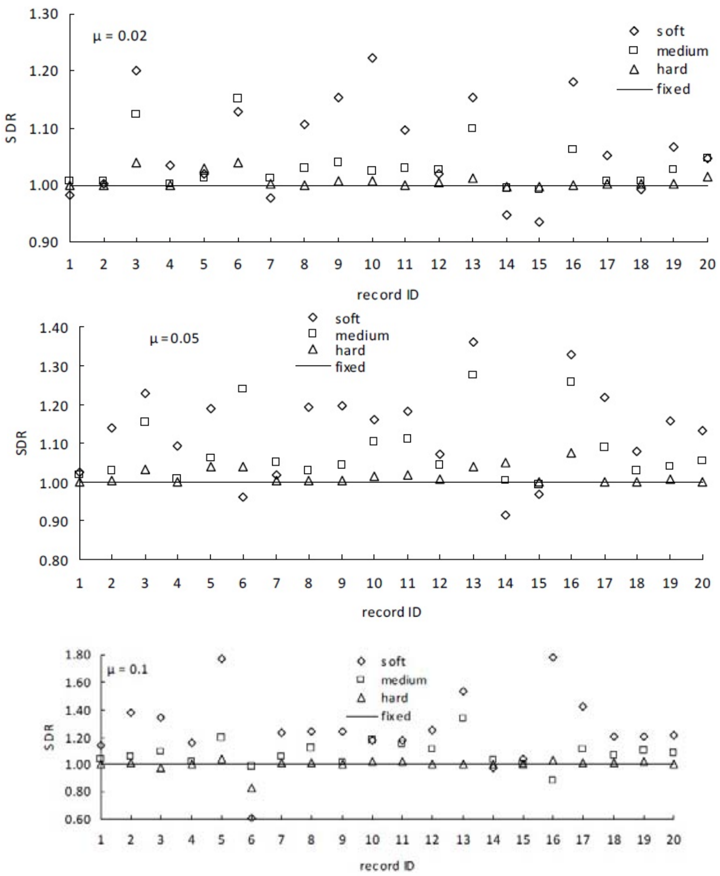

Fig. 2 Sliding displacement ratio (SDR) versus seismic motion number for NF earthquakes

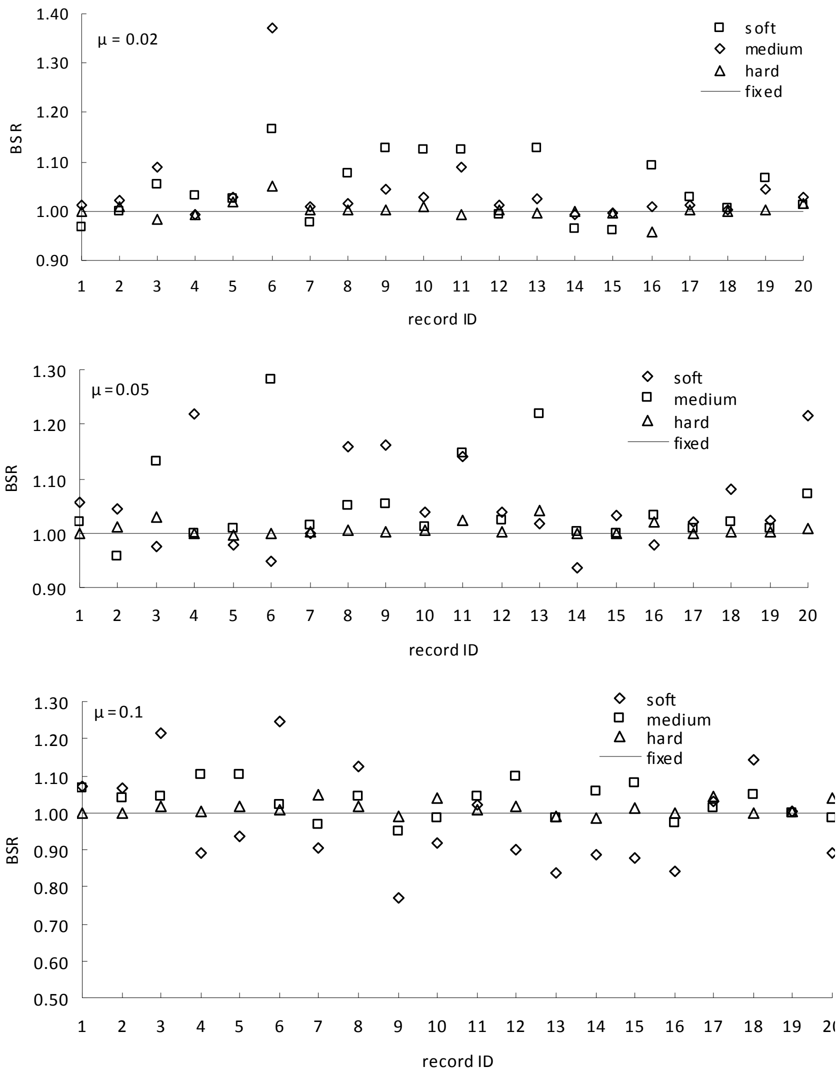

Fig. 3 Base shear ratio (BSR) versus seismic motion number for NF earthquakes

Table 2 Sliding displacement response for NF earthquake

	μ = 0.02				μ = 0.05				μ = 0.10			
EQ.No	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*
1	375.3	384.6	381.9	382.1	342.7	340.4	334.9	334.5	287.0	261.8	252.7	251.8
2	248.1	249.6	247.7	247.7	214.1	193.8	188.6	188.2	173.4	132.8	126.6	125.7
3	67.2	62.9	59.3	55.9	42.8	40.1	36.0	34.8	33.3	27.2	24.2	24.8
4	387.9	376.0	375.1	375.2	377.6	348.1	345.4	345.9	364.2	320.1	315.4	314.2
5	120.9	119.9	121.9	118.5	97.0	86.6	86.6	81.6	78.2	52.8	54.1	44.2
6	68.8	70.1	69.1	61.0	38.7	49.8	43.2	40.2	20.2	32.5	27.5	33.0

Table 2 Continued

7	356.9	369.1	366.1	365.2	309.8	319.1	305.8	304.4	263.7	226.5	216.9	214.6
8	222.5	207.0	201.2	201.4	174.4	150.3	146.5	146.0	143.3	129.9	117.1	115.9
9	299.3	269.8	261.1	259.4	280.5	244.6	235.8	234.7	243.8	199.4	197.0	196.3
10	135.4	113.3	111.4	110.7	121.0	114.9	105.6	104.1	107.9	107.3	93.7	91.4
11	249.8	234.9	228.0	228.1	221.7	208.4	191.4	187.8	189.2	185.0	165.0	161.2
12	343.2	345.5	337.8	336.6	295.9	287.3	278.2	275.8	218.2	194.5	176.3	175.1
13	97.7	93.2	85.7	84.8	55.4	51.9	45.4	40.7	44.1	38.4	28.8	28.7
14	430.8	452.7	454.1	455.0	378.5	415.1	413.2	413.5	341.7	359.3	349.3	348.7
15	497.9	527.8	531.0	532.6	465.3	478.3	480.4	481.2	415.6	403.9	401.4	401.3
16	58.4	52.5	49.4	49.5	37.7	23.4	18.9	17.6	18.4	8.4	13.2	9.5
17	202.0	193.6	192.8	192.2	170.4	152.5	140.2	140.1	156.5	121.7	110.5	109.6
18	238.6	242.1	240.9	240.7	227.2	216.6	211.1	211.0	170.2	151.0	143.5	141.2
19	279.8	268.9	263.0	262.2	180.7	162.5	157.2	156.3	138.2	126.6	116.3	114.4
20	213.9	214.1	207.4	204.4	184.9	172.5	163.8	163.5	134.2	119.5	110.8	110.3

(*S*: soft, *M*: medium, *H*: hard, *F*: fixed)

Table 3 Base shear response for NF earthquake

	μ = 0.02				μ = 0.05				μ = 0.10			
EQ.No	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*
1	144.0	151.0	149.0	149.0	148.0	143.0	140.0	140.0	144.1	129.5	126.8	126.2
2	98.0	100.0	99.0	98.0	96.0	88.0	93.0	92.0	115.0	98.6	96.2	95.6
3	30.0	31.0	28.0	28.5	37.0	43.0	42.0	38.0	53.6	76.1	71.6	71.4
4	150.6	145.0	145.0	146.0	168.0	138.0	138.0	138.0	186.2	153.2	147.0	146.7
5	52.3	52.4	51.9	50.9	53.5	55.3	54.7	54.8	67.7	62.5	71.1	64.3
6	34.4	40.4	32.8	29.5	39.5	53.4	41.6	41.6	55.4	81.5	69.8	68.7
7	141.4	145.9	144.9	144.6	135.9	137.7	136.2	135.9	136.2	120.8	118.8	118.7
8	90.2	84.9	83.9	83.7	84.9	76.8	73.6	73.2	108.3	102.3	97.4	96.6
9	119.3	110.4	105.9	105.7	121.1	109.8	104.6	104.2	125.5	106.9	104.6	103.9
10	59.1	54.1	53.1	52.6	66.6	65.0	64.6	64.3	78.6	77.7	80.7	77.4
11	106.4	103.1	94.1	94.6	106.3	107.0	95.4	93.3	124.0	139.1	129.1	117.0
12	132.1	134.5	133.2	133.0	127.8	125.6	123.2	122.9	117.9	112.5	106.3	106.8
13	45.7	41.4	40.2	40.4	42.4	50.9	47.8	41.8	56.4	75.3	71.0	64.8
14	170.2	175.1	176.2	176.6	162.1	173.1	172.9	172.9	178.8	181.6	176.2	176.0
15	195.3	202.3	202.8	203.4	200.5	193.9	193.8	194.0	206.2	191.3	190.3	189.8
16	28.8	26.6	25.3	26.4	34.2	36.1	35.7	35.0	44.7	55.4	61.1	57.6
17	84.7	83.3	82.7	82.4	82.4	81.3	80.7	80.7	93.1	84.5	81.5	81.2
18	99.1	98.6	98.5	98.4	104.2	98.5	96.7	96.4	101.7	99.0	95.1	95.3
19	111.4	109.1	104.8	104.5	81.4	80.3	79.7	79.6	92.3	88.2	82.0	80.7
20	85.8	87.0	85.8	84.6	93.6	82.5	77.5	76.9	103.1	99.1	94.6	95.6

(*S*: soft, *M*: medium, *H*: hard, *F*: fixed)

Table 4 Sliding displacement response for FF earthquake

	μ = 0.02				μ = 0.05				μ = 0.10			
EQ.No	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*
1	116.7	110.0	108.6	108.4	111.0	95.8	89.1	88.3	82.4	68.5	58.7	58.0
2	85.2	62.8	62.7	62.5	54.9	44.8	40.2	40.2	49.7	36.6	32.8	33.0
3	134.3	136.3	133.2	133.0	123.3	110.0	102.8	101.6	99.5	69.9	58.5	57.5
4	59.2	62.4	60.9	60.6	41.8	28.8	28.3	28.0	22.2	27.6	23.3	23.4
5	72.7	75.4	70.4	69.3	68.5	61.8	61.3	60.0	60.2	52.2	49.1	48.2
6	146.8	149.5	145.1	146.1	132.0	124.5	120.1	116.9	94.6	61.9	50.4	48.5
7	89.0	89.7	84.7	84.4	67.8	66.7	57.5	56.3	53.2	45.8	44.1	44.5
8	134.0	134.2	131.9	131.4	100.9	91.1	85.3	84.1	64.6	53.4	40.0	38.9
9	59.5	51.9	49.5	48.6	38.3	40.3	34.6	34.0	31.3	28.3	26.2	26.1
10	62.4	54.8	54.0	53.7	42.7	44.4	37.6	36.2	36.1	42.7	38.4	37.7
11	34.0	35.5	27.2	26.0	19.1	23.0	18.6	18.2	0.0	2.9	3.3	3.8
12	46.7	43.1	41.3	40.8	40.4	24.3	26.9	26.5	15.5	24.2	10.6	8.8
13	90.8	77.4	71.5	70.9	62.6	50.7	50.3	50.0	16.8	34.3	24.0	22.9
14	103.9	94.1	92.8	92.8	41.8	25.1	20.5	20.0	30.3	31.7	23.0	21.2
15	85.6	82.2	80.7	80.3	64.4	60.3	54.7	54.6	6.6	17.7	15.3	14.7
16	67.4	57.8	56.5	56.3	17.2	10.4	6.5	6.3	17.8	22.2	20.0	17.8
17	82.7	76.1	74.5	74.3	44.8	30.4	27.3	27.2	45.8	33.9	32.2	30.0
18	76.0	64.5	66.4	66.0	50.5	49.2	43.3	43.1	38.2	30.5	23.8	21.8
19	182.0	148.1	141.8	141.3	170.1	145.1	140.8	140.6	157.3	146.9	140.2	139.2
20	103.1	88.6	85.8	85.7	71.1	50.5	50.5	51.3	33.7	31.2	28.3	26.3

(*S*: soft, *M*: medium, *H*: hard, *F*: fixed)

Table 5 Base shear response for FF earthquake

	μ =0.02				μ =0.05				μ =0.10			
EQ.No	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*	*S*	*M*	*H*	*R*
1	49.8	46.0	46.2	46.2	63.1	53.5	49.8	49.1	72.3	72.0	67.4	67.5
2	40.5	31.0	31.3	31.3	44.3	43.0	41.4	41.4	66.0	64.4	61.8	61.9
3	54.9	57.8	58.4	58.4	65.0	57.5	54.0	53.7	78.8	67.7	65.8	64.8
4	31.2	31.9	32.1	32.0	35.0	35.4	32.3	32.6	48.1	59.4	54.2	54.0
5	37.3	37.6	32.2	31.8	40.9	41.5	47.2	48.1	59.0	69.5	64.0	63.0
6	65.3	64.6	62.9	63.3	75.4	69.5	67.0	72.1	75.5	61.9	61.1	60.7
7	43.5	41.0	40.5	40.4	44.5	56.9	43.2	44.1	61.2	65.2	73.5	67.6
8	58.4	60.7	59.6	59.5	54.9	51.6	50.4	50.6	69.6	64.5	63.0	61.8
9	27.6	27.4	28.4	26.8	31.5	39.9	37.8	36.9	40.7	50.0	52.1	52.8
10	31.6	28.9	29.9	30.2	31.2	37.1	37.7	35.9	56.3	60.4	63.5	61.2
11	22.0	26.6	19.7	18.9	31.6	41.4	38.0	37.9	49.7	50.2	48.6	48.1
12	26.9	24.8	23.1	22.9	31.6	41.4	38.0	36.4	42.9	52.4	48.6	47.7
13	47.4	36.9	33.7	33.5	51.3	47.5	44.5	45.0	48.8	57.4	57.8	58.3

Table 5 Continued

14	46.3	42.8	42.4	42.4	35.0	31.9	31.4	30.0	47.9	57.1	53.4	54.1
15	39.5	38.1	37.5	37.4	46.2	45.2	46.5	46.8	53.2	65.5	61.3	60.5
16	25.6	29.0	27.8	28.2	32.1	28.8	28.2	27.4	48.9	56.6	58.3	58.2
17	37.2	34.8	35.5	35.4	35.4	34.5	31.7	31.2	60.3	59.3	61.2	58.6
18	37.6	34.9	34.6	34.5	41.4	39.7	36.3	36.2	56.0	51.6	49.1	49.1
19	77.9	65.1	62.6	62.3	88.0	77.5	76.1	75.8	102.1	101.7	102.1	101.8
20	47.2	41.4	39.7	40.3	53.8	42.7	42.6	42.1	53.1	58.8	64.5	59.5

(*S*: soft, *M*: medium, *H*: hard, *F*: fixed)

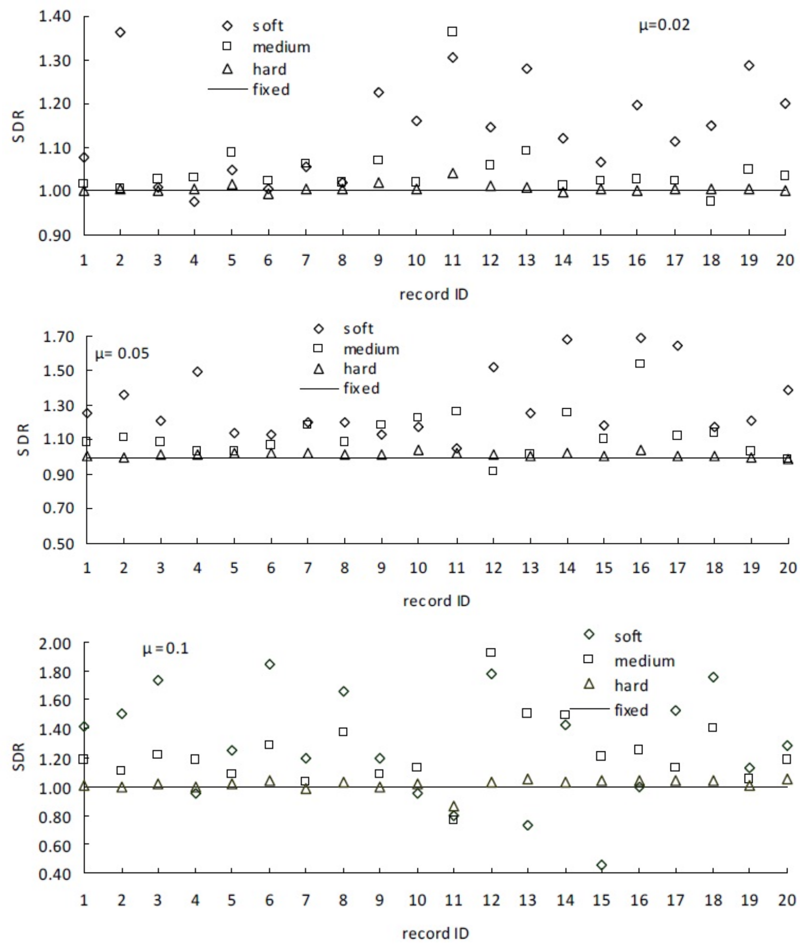

Fig. 4 Sliding displacement ratio (SDR) versus seismic motion number for FF earthquakes

increases due to SSI. This clearly shows that the sliding displacement and base shear are under-estimated if SSI effects are ignored in the analysis of structures isolated by FPS. However, in the case of structure on hard soil, only few ground motions affect the response of the structure. The maximum increase or decrease in SDR or BSR due to SSI in this case is lesser than 5%. This indicates that as expected, the SSI has no much effect on the response of structures on hard soils. It can also be observed from the figures and tables that for similar values of friction coefficients, more number of earthquake ground motions affect the sliding displacement compared to the base shear. This investigation also shows that the effect of SSI on response of the structure is influenced considerably by the friction coefficient μ of sliding material. It is observed from the table that for the range of friction coefficients considered, the SSI effect is more when μ = 0.1 compared to the SSI effect when μ = 0.02 or μ = 0.05 for similar type of soil. In majority of the cases, the number of NF set of ground motions producing unfavourable SSI effect is observed to be more compared to the number of FF set of ground motions producing unfavourable SSI effect. In addition, the above observation also show that, for the present study, the effect of SSI is more pronounced for FF set of ground motions when compared to NF set of ground motions.

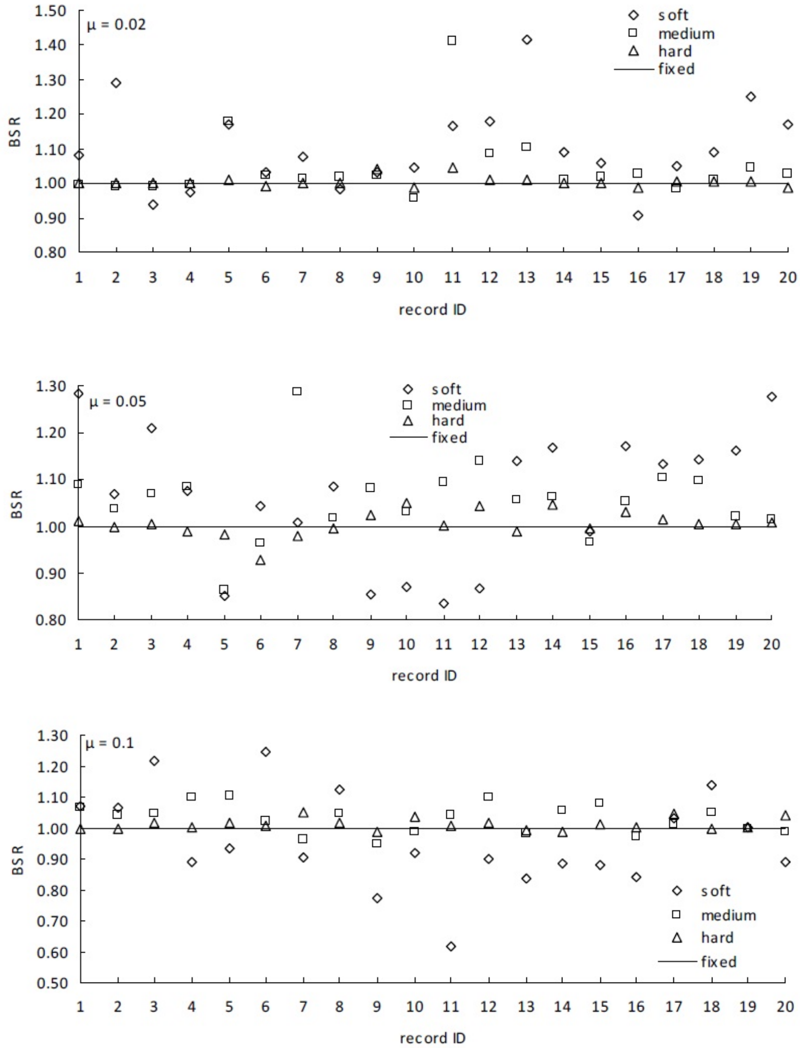

Fig. 5 Base shear ratio (BSR) versus seismic motion number for FF earthquakes

5. Conclusions

The effect of soil structure interaction (SSI) is studied on the response of a multi-degree-of-freedom structure seismically isolated with sliding bearing using friction pendulum system (FPS). In the analysis the soil is modeled as an elastic continuum and the finite element method is used to model the soil, foundation and structure. In order to study the SSI effect for ground motions of varying intensity and frequency, the seismically isolated structure with SSI is subjected to twenty FF and twenty NF ground motions. Three types of soils namely soft, medium and hard soils are considered for the study. In addition, the influence of friction coefficients of sliding material on SSI effect is also studied. From the study it is concluded that SSI affects the response of a structure isolated with FPS. In majority of the cases, the sliding displacement and base shear are underestimated if SSI effects are ignored in the analysis of structures isolated with FPS. However in some cases, depending on friction coefficients of sliding material and type of ground motions, SSI may also be beneficial for the isolated structure. Also, SSI effects are more pronounced for soft and medium soils and SSI effect decreases as the stiffness of soil increases. SSI effects are also influenced by coefficient of friction of sliding material of FPS. For effective design of structures isolated with FPS, inclusion of SSI is essential especially when it is supported on soft and medium soils.

References

Chaudhary, M.T.A., Abe, M. and Fujino, Y. (2001), "Identification of soil – structure interaction effect in base – isolated bridges from earthquake records", *Soil Dyn. Earthq. Eng.*, **21**(8), 713-725.

Dicleli, M., Albhaisi, S. and Mansour, M.Y. (2005), "Static soil-structure interaction effects in seismic–isolated bridges", *Practice period. Struct. Des. Constr*., **10**(1), 22-33.

Eröz, M. and DesRoches, R. (2008), "Bridge seismic response as a function of the friction pendulum system (FPS) modeling assumptions", *Eng. Struct.*, **30**(11), 3204-3212.

Maheshwari, B.K., Truman, K.Z., Gould, P.L. and Naggar, M.H. (2005), "Three – dimensional nonlinear seismic analysis of single piles using finite element model: effects of plasticity of soil", *Int. J. Geomech., ASCE,* **5**(1), 35- 44.

Mostaghel, N. and Tanbakuchi, J. (1983), "Response of sliding structures to earthquake support motion", *Earthq. Eng. Struct. Dyn.*, **11**(6), 729-748.

Novak, M. and Mitwally, H. (1988), "Transmitting boundary for axisymmetrical dilation problems", *J. Eng. Mech.- ASCE,* **114**(1), 181-187.

Soneji, B.B. and Jangid, R.S. (2008), "Influence of soil-structure interaction on the response of seismically isolated cable-stayed bridge", *Soil Dyn. Earthq. Eng.*, **28**(4), 245-257.

Spyrakos, C.C. and Loannidis, G. (2003), "Seismic behaviour of a post – tensioned integral bridge including soil – structure interaction (SSI)", *Soil Dyn. Earthq. Eng.,* **23**(1), 53-63.

Stehmeyer, E.H. and Rizos, D.C. (2008), "Considering dynamic soil structure interaction (SSI) effects on seismic isolation retrofit efficiency and the importance of natural frequency ratio", *Soil Dyn. Earthq. Eng.*, **28**(6), 468-479.

Takewaki, I., Nakamura, T. and Hirayama, K. (1998), "Seismic frame design via inverse mode design of frame-ground systems", *Soil Dyn. Earthq. Eng.*, **17**(3), 153-163.

Takewaki, I. (1998), "Remarkable response amplification of building frames due to resonance with the surface ground", *Soil Dyn. Earthq. Eng.*, **17**(4), 211-218.

Takewaki, I. (2005a), "Frequency domain analysis of earthquake input energy to structure-pile systems", *Eng. Struct.*, **27**(4), 549-563.

Takewaki, I. (2005b), "Bound of earthquake input energy to soil-structure interaction systems", *Soil Dyn. Earthq. Eng.*, **25**(7-10), 741-752.
Tongaonkar, N.P. and Jangid, R.S. (2003), "Seismic response of isolated bridges with soil – structure interaction", *Soil Dyn. Earthq. Eng.*, **23**(4), 287-302.
Ucak, A. and Tsopelas, P. (2008), "Effect of soil – structure interaction on seismic isolated bridges", *J. Struct. Eng.-ASCE*, **134**(7), 1154-1164.
Vafai, A., Hamidi, M. and Ahmadi, G. (2001), "Numerical modeling of MDOF structures with sliding supports using rigid – plastic link", *Earthq. Eng. Struct. Dyn.*, **30**(1), 27-42.
Vlassis, A.G. and Spyrakos, C.C. (2001), "Seismically isolated bridge piers on shallow soil stratum with soil structure interaction", *Comput. Struct.*, **79**(32), 2847-2861.
Yang, Y.B., Lee, T.Y. and Tsai, I.C. (1990), "Response of multi - degree – of – freedom structures with sliding supports", *Earthq. Eng. Struct. Dyn.*, **19**(5), 739-752.
Zayas, V.A., Low, S.S. and Mahin, S.A. (1990), "A simple pendulum technique for achieving seismic isolation", *Earthq. Spectra*, **6**(2), 317-333.

IT