SEISMIC ISOLATION OF TORSIONALLY COUPLED MACHINE FOUNDATION CONSIDERING SOIL-STRUCTURE INTERACTION

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by

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Dedicated to my family and friends

CERTIFICATE

This is to certify that the thesis titled, **"SEISMIC ISOLATION OF TORSIONALLY COUPLED MACHINE FOUNDATION CONSIDERING SOIL-STRUCTURE INTERACTION"** being submitted by **Mr. Rajkumar K** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. He worked under our supervision for the submission of thesis, which to our knowledge has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

Further, the contents of his research work, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma to the best of our knowledge and belief.

New Delhi
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ABSTRACT

Machine foundations are inevitable components of any industrial infrastructure which helps in distribution of the machine loads and mitigation of vibrations developed due to the rotating machine parts. Soil conditions and the types of foundation which support these machines play an important role in ensuring safe design and performance of different machines. Framed-type machine foundations also known as turbo-generator (TG) foundations are the common supporting system for rotary machines of medium to high-speed (Barkan, 1962; Arya et al., 1979; BIS, 1992; Srinivasulu and Vaidyanathan, 1980; Bhatia, 2008). In general, the permissible displacement amplitude of vibration for the framed-type machine foundations supporting rotary machine is very low (Blake, 1964; Baxter and Bernhard, 1967; Richart et al., 1970; Prakash and Puri, 1988; BIS, 1992; ACI, 2004; Das and Ramana, 2010). When vibration control devices (base isolation techniques) are used, the design approaches for the machine foundations considering torsional effects (due to eccentricities between center of rigidity and center of mass) are still in the development stage. Especially, the effects of flexibility of underlying soil in combination with torsional coupling is ignored in the designs. In machine foundations, dynamic loads always exist and the energy content of this force is transmitted to the supporting soil through foundation system. This energy travels in all directions into the soil and part gets absorbed by the soil itself, part reflects back to the foundation and thereby into the machine. This cyclic process initiates Soil-Structure Interaction (SSI), which significantly influences the dynamic response of the machine foundation (Mayerhof, 1953; Gazetas, 1983; Wolf, 1997; Biswas and Manna, 2018). The present research work investigates the effects of base isolation devices used in torsionally coupled machine foundations while duly considering SSI in to account.

Observations of damages on structures after recent earthquakes have shown the importance of torsional vibrations, induced by lateral seismic ground motions. Eccentricity between the center of mass (CM) and the center of rigidity (CR) may lead to torsional coupling in framed structures (Danisch and Labes, 1976; Reinhorn et al., 1977; Eisenberger and Rutenberg, 1985; Chandler and Hutchinson, 1986; Kelly, 1986; Rutenberg and Pekau, 1987; Chandler and Hutchinson, 1992; Jiang and Hutchinson, 1993; Jangid and Datta, 1995; Jangid and Kelly, 2000; Kilar and Koren, 2009; Matsagar and Jangid, 2010; Trifunac, 2013). Asymmetries are quite common in framed-type machine foundations supporting

rotary machines as it consists many cut-outs (openings) in deck slab. Also, the layout of equipment and its accessories (such as heavy turbine, generator, gear box, equipment oil system, condenser etc.) on deck slab are quite complex and its arrangement are also not symmetrical. This would lead to prevalence of torsional coupling in most turbine machine foundations. In addition, geometrical imperfections in the form of initial curvature or bend, i.e. out-of-plumb are possible during construction of slender columns. Slender columns are very common in the framed-type machine foundations supporting rotary machines, and hence the imperfections in the form of initial bend are possible. These initial geometrical imperfections in general, reduce the load-carrying capacity of the structure/foundation under static loads. In addition, these imperfections may alter the stiffness of columns, which may eventually affect the dynamic response of structures/foundations (Chajes, 1974; Celep, 1985; Souza, 1987; Yaoshun et al., 1998; Dubina and Ungureanu, 2002; and Sovizi et al., 2010; Sharma et al., 2014; Jain and Rai, 2014; Shayan et al., 2014; Cardoso and Rasmussen, 2016; Monsalve-Giraldo et al., 2017; Marinca and Herisanu, 2018; De Domenico et al., 2018; Dhar et al., 2018). Hence, the main sources of asymmetries in framed-type machine foundation considered here are due to variation in the stiffness provided by columns (construction defects) and due to uneven distribution of machine mass on the deck slab.

Improper functioning of sensitive equipments, disturbances to people and visible structural damage may occur due to dynamic effects of machines, especially in industries (ACI, 2004). The base isolation concept is mainly used to decouple the machine vibrations and seismic ground motion from its foundation. Using the base isolation technique, the structure is isolated from the vibrations by insertion of flexible layer, which is formed by elastomeric and/or sliding bearings. Such flexibility elongates time period, thereby reduce seismic forces. Moreover, the bearings provide additional means of energy dissipation through high damping (Jangid and Datta, 1995; Jangid and Kelly, 2000; Matsagar and Jangid, 2005; Bhat and Paul, 2016; Konstantinidis, 2018; Terazawa and Takeuchi, 2018). The aim of vibration isolation of machine foundation is to prevent transmission of vibrations from the machine or from ground. The foundation is designed to avoid resonance with the machine vibrations and also against seismic ground motions. However, in most cases, the effect of soil flexibility and torsional effects are ignored in the machine foundation design. The proposed doctoral research will greatly contribute in the advancement of current knowledge in the design of machine foundations and vibration mitigation therein, considering the effects of torsional coupling, geometrical imperfection and SSI.

सार

मशीन की नींव किसी भी औद्योगिक अवसंरचना के अपरिहार्य घटक हैं जो घूमने वाली मशीन के पुर्जों के कारण विकसित किए गए कंपन के मशीन भार और शमन के वितरण में मदद करते हैं। मिट्टी की स्थिति और नींव के प्रकार जो इन मशीनों का समर्थन करते हैं, विभिन्न मशीनों के सुरक्षित डिजाइन और प्रदर्शन को सुनिश्चित करने में महत्वपूर्ण भूमिका निभाते हैं। फ़्रेम-टाइप मशीन फ़ाउंडेशन जिन्हें टर्बो-जनरेटर (टीजी) फ़ाउंडेशन के रूप में भी जाना जाता है, मध्यम से हाईस्पीड (बार्कन, 1962; आर्य एट अल।, 1979; 1979; बीआईएस, 1992; श्रीनिवासुलु और वैद्यनाथन,1980; भाटिया, 2008) की रोटरी मशीनों के लिए सामान्य सहायक प्रणाली है। सामान्य तौर पर, अनुमेय विस्थापन आयाम कंपन के लिए रोटरी मशीन का समर्थन करने वाले फ़्रेम-प्रकार की मशीन नींव बहुत कम है (ब्लेक, 1964; बैक्सटर और बर्नहार्ड, 1967; रिचर्ड एट अल, 1970; प्रकाश और पुरी, 1988; बीआईएस, 1992; एसीआई; 2004; दास और रमना, 2010)। जब कंपन नियंत्रण उपकरणों (आधार (बेस) अलगाव (आइसोलेशन) तकनीकों) का उपयोग किया जाता है, तो मशीन नींव के लिए डिज़ाइन दृष्टिकोण टॉर्सनल प्रभाव (कठोरता के केंद्र (सेंटर) और द्रव्यमान के केंद्र के बीच विलक्षणता (एक्सेंट्रिसिटीस) के कारण) के विकास के चरण में होते हैं। विशेष रूप से, मरोड़ वाले (टॉर्स्ीओनल) कपलिंग) के साथ अंतर्निहित मिट्टी के लचीलेपन (फ्लेक्सिबिलिटी) के प्रभावों को डिजाइनों में अनदेखा किया जाता है। मशीन नींव में, गतिशील भार (डाइनमिक लोड्स) हमेशा मौजूद होता है और इस बल की ऊर्जा सामग्री नींव प्रणाली के माध्यम से सहायक मिट्टी में संचारित होती है। यह ऊर्जा मिट्टी में सभी दिशाओं में यात्रा (ट्रॅवेल्ज़) करती है और भाग मिट्टी से ही अवशोषित (अब्ज़ॉर्ब्ड) हो जाता है, भाग नींव (फाउंडेशन) में और इस तरह मशीन में वापस आ जाता है। यह चक्रीय प्रक्रिया मृदा-संरचना सहभागिता (सोइल-स्ट्रक्चर इंटरॅक्षन) (एसएसआई) की शुरुआत करती है, जो मशीन नींव की गतिशील प्रतिक्रिया को काफी प्रभावित करती है (मेयरहोफ, 1953; गज़ेटास, 1983; वुल्फ; 1997; विश्वास और मन्ना, 2018)। वर्तमान शोध कार्य एसएसआई को ध्यान में रखते हुए विधिवत रूप से युग्मित मशीन नींव (टॉर्स्ीओनल्ली कपल्ड मशीन फाउंडेशन्स) में उपयोग किए गए आधार अलगाव (बेस आइसोलेशन) उपकरणों के प्रभावों की जांच करते हैं।

हाल के भूकंपों के बाद संरचनाओं पर नुकसान की टिप्पणियों ने टॉर्सनल कंपन (वाइब्रेशन्स) के महत्व को दर्शाया है, जो पार्श्व भूकंपीय गति (लॅटरल सेसमिक ग्राउंड मोशन्स) से प्रेरित है। द्रव्यमान के केंद्र (सीयेम) और कठोरता के केंद्र (सीआर) के बीच विलक्षणता फ़्रेमयुक्त संरचनाओं में मरोड़ वाले युग्मन को जन्म दे सकती है (डैनिश एंड लेबल्स, 1976; आइनेहॉर्न एट अल, 1977; ईसेनबर्गर एंड रुटेनबर्ग, 1985; चैंडलर और हचिंसन, 1986; केली, 1986; रुटेनबर्ग और पेकाऊ, 1987; चैंडलर और हचिंसन, 1992; जियांग और हचिंसन, 1993;

जांगिड और दत्ता, 1995; जांगिड और केली, 2000; किलर और कोरेन, 2009; मतसागर और जांगिड, 2010; ट्रिफुनाक, 2013)। रोटरी मशीनों का समर्थन करने वाले फ्रेम-प्रकार की मशीन नींव में असममितता (एसिमेट्रीस) काफी आम है क्योंकि इसमें डेक स्लैब में कई कट-आउट (उद्घाटन/ओपनिंग्स) होते हैं। इसके अलावा, डेक स्लैब पर उपकरण और उसके सामान (जैसे भारी टरबाइन, जनरेटर, गियर बॉक्स, उपकरण तेल प्रणाली (एक्विपमेंट आयिल), कंडेनसर आदि) का लेआउट काफी जटिल है और इसकी व्यवस्था भी सममित (सिम्मेट्रिकल) नहीं है। यह सबसे टरबाइन मशीन नींव में मरोड़ युग्मन का प्रसार होगा। इसके अलावा, प्रारंभिक वक्रता (इनिशियल कर्वेचर) या मोड़ (बेंड) के रूप में ज्यामितीय खामियां (जीयोमीट्रिकल इमपर्फेक्षन्स), यानी पतले स्तंभों (स्लेंडरर कॉलम्स) के निर्माण के दौरान आउट-ऑफ-प्लंब संभव है। रोटरी मशीनों का समर्थन करने वाले फ्रेम-प्रकार की मशीन नींव में पतले स्तंभ बहुत आम हैं, और इसलिए प्रारंभिक मोड़ के रूप में खामियां संभव हैं। सामान्य रूप से ये प्रारंभिक ज्यामितीय खामियां, स्थिर भार (स्टॅटिक लोड्स) के तहत संरचना / नींव की भार-वहन क्षमता (लोड-कॅरीयिंग केपॅसिटी) को कम करती हैं। इसके अलावा, ये खामियां स्तंभों की कठोरता (स्टिफनेस) को बदल सकती हैं, जो अंततः संरचनाओं / नींव की गतिशील प्रतिक्रिया (डाइनमिक रेस्पॉन्स) को प्रभावित कर सकती हैं (चेज़्स, 1974; सेलेप; 1985; सूजा; 1987; यशुन एट अल, 1998; डबीना और उनगुरानू, 2002; और सोविज़ी एट अल, 2010; शर्मा एट अल, 2014; जैन और राय, 2014; श्यान एट अल, 2014; कार्डसो और रासमुसेन, 2016; मोनसालवे-गिराल्डो एट अल, 2017; मारिंका और हरिसनू, 2018; डी डोमिनिको एट अल, 2018; धार एट अल, 2018)। इसलिए, फ्रेम-प्रकार की मशीन में असममितता के मुख्य स्रोत हैं यहां माना जाने वाला आधार स्तंभों (निर्माण दोष) द्वारा प्रदान की गई कठोरता में भिन्नता के कारण और डेक स्लैब पर मशीन द्रव्यमान के असमान वितरण के कारण होता है।

संवेदनशील उपकरणों (सेन्सिटिव एक्विपमेंट्स) के बेहतर कामकाज, लोगों को गड़बड़ी और दिखाई संरचनात्मक क्षति (स्ट्रक्चरल डॅमेज), मशीनों के गतिशील प्रभावों के कारण हो सकती है, विशेष रूप से उद्योगों (इंडस्ट्रीस) (एसीआई, 2004) में। आधार अलगाव (बेस आइसोलेशन) अवधारणा का उपयोग मुख्य रूप से मशीन कंपन और भूकंपीय जमीन की गति को इसकी नींव से अलग करने के लिए किया जाता है। बेस आइसोलेशन तकनीक का उपयोग करते हुए, संरचना को लचीली परत (फ्लेक्सिबल लेयर) के सम्मिलन से कंपन से अलग किया जाता है, जो इलास्टोमेरिक द्वारा बनाई जाती है और / या फिसलने (स्लाइडिंग) बीयरिंग। इस तरह की लचीलापन समय अवधि (टाइम पीरियड) को बढ़ाती है, जिससे भूकंपीय बलों को कम किया जा सकता है। इसके अलावा, बीयरिंग उच्च भिगोना (हाइ डॅंपिंग) के माध्यम से ऊर्जा अपव्यय (एनर्जी डिसिपेशन) के अतिरिक्त साधन प्रदान करते हैं (जांगिड और दत्ता, 1995; जांगिड़ और केली, 2000; मतसागर और जांगिड, 2005; भट

और पॉल, 2016; कौंस्टेंटिनिडिस, 2018; तराज़वा और टेकुची, 2018)। मशीन फाउंडेशन के कंपन अलगाव का उद्देश्य मशीन से या जमीन से कंपन के संचरण को रोकना है। नींव को मशीन के कंपन के साथ गूंज (रेज़नेन्स) से बचने के लिए और भूकंपीय जमीन की गति के खिलाफ भी बनाया गया है। हालांकि, ज्यादातर मामलों में, मशीन नींव डिजाइन में मिट्टी के लचीलेपन और मरोड़ वाले प्रभावों की अनदेखी की जाती है। प्रस्तावित डॉक्टरेट अनुसंधान मशीन नींव और कंपन शमन के डिजाइन में वर्तमान ज्ञान की उन्नति में बहुत योगदान देगा, जो टॉर्सनियल युग्मन, ज्यामितीय अपूर्णता और एसएसआई के प्रभावों पर विचार करेगा।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

MATHEMATICAL NOTATIONS

$[C]$	Damping matrix
$[K]$	Stiffness matrix
$[M]$	Mass matrix
$\{\ddot{z}\}$	Acceleration vector in vertical direction
$\{\dot{z}\}$	Velocity vector in vertical direction
$\{z\}$	Displacement vector in vertical direction
A	Dimensionless parameter used in Wen's model
A_{p}	Cross-sectional area of pile
E_{p}	Modulus of elasticity of the pile
F_0	Normalized yield strength of the base isolator or unbalanced dynamic force from rotary machine
$F(t)$	Unbalanced dynamic force
F_{b}	Restoring force of the base isolator
F_{u}	Unbalanced vertical force
F_{xb}	Restoring force of the base isolator in *x*-direction
F_{yb}	Restoring force of the base isolator in *y*-direction
$F_{\theta\mathrm{b}}$	Torsional force in isolation system
F_{y}	Bearing yield strength of the base isolator
G	Shear modulus of the soil
I_{f}	Moment of inertia of the foundation raft
I_{u}	Kinematic displacement factor
K	Stiffness of column
K_{xs}	Stiffness of superstructure in *x*-direction

K_{ys}	Stiffness of superstructure in *y*-direction
$K_{\theta s}$	Torsional stiffness of superstructure
L	Length of column
M	Total mass of the base-isolated machine foundation
N	Operating speed of rotary machine
N	Load from longitudinal beam
P	Concentrated machine load or applied axial load
P_0	Initial axial load
P_E	Euler buckling load
$P_z(t)$	Unbalanced vertical dynamic force
Q	Self-weight of the beam
Q_0	Initial transverse load
T_b	Time period of the base isolator
T_s	Time period of the framed-foundation
U_p	Pile response at top
U_{ff}	Amplitude of free-field motion
W	Total weight of the base-isolated machine foundation
Z	Non-dimensional hysteretic displacement
a	Equivalent radius of circular footing and initial imperfection amplitude
a_0	Dimensionless frequency ratio
a_{01}	Dimensionless frequency ratio factor
a_{02}	Dimensionless frequency ratio factor
a_p	Pile diameter
d	Diameter of column or pile
c_1	Damping of beam or damping of first degree of freedom

c_2	Damping of column or damping of second degree of freedom
c_{b}	Damping of the base isolator in horizontal direction
c_{h}	Damping of the foundation-soil in horizontal direction
c_{s}	Damping of the superstructure in horizontal direction
c_{z}	Damping of the foundation-soil in vertical direction
c_{θ}	Damping of the foundation-soil in rocking direction
e	Eccentricity
e_{r}	Eccentricity ratio
e_{xb}	Eccentricity between the center of mass and the center of rigidity of the isolation system in *x*-direction
e_{xs}	Eccentricity between the center of mass and the center of rigidity of the column in *x*-direction
e_{yb}	Eccentricity between the center of mass and the center of rigidity of the isolation system in *y*-direction
e_{ys}	Eccentricity between the center of mass and the center of rigidity of the column in *y*-direction
f_{m}	Operating frequency
f_{n}	Natural frequency
f_1	Stiffness parameter for homogeneous soil
f_2	Damping parameter for homogeneous soil
f_{n1}	Natural frequency in lateral mode
f_{n2}	Natural frequency in torsional mode
f_{n3}	Natural frequency in vertical mode
f_{xbj}	Isolation force in j^{th} bearing developed in *x*-direction
f_{ybj}	Isolation force in j^{th} bearing developed in *y*-direction

h	Foundation to deck height or height of column
k_1	Flexural stiffness of beam or stiffness of first degree of freedom
k_2	Axial stiffness of column or stiffness of second degree of freedom
k_b	Post-yield stiffness of the base isolator in horizontal direction
k_h	Stiffness of the soil in horizontal direction
k_s	Stiffness of the frame in horizontal direction
k_z	Stiffness of the foundation-soil in horizontal direction
k_θ	Stiffness of the foundation-soil in rocking direction
k_xi	Lateral stiffness of i^{th} column in *x*-direction
k_yi	Lateral stiffness of i^{th} column in *y*-direction
m	Mass
m_0	Lumped mass of raft foundation
m_1	Lumped mass of beam or first degree of freedom
m_2	Lumped mass of column or second degree of freedom
m_u	Unbalanced mass
m_b	Lumped mass of the base raft including base isolator
m_f	Lumped mass of the foundation raft
m_r	Mass moment of inertia of the foundation raft
m_s	Lumped mass of the deck including machine
m_t	Total mass
n	Integer constant controlling nonlinearity
q	Bearing yield displacement of the base isolator
r_0	Radius of the pile
r_s	Radius of gyration of deck
r_s	Radius of gyration of base raft

t	Time
u_{x}	Lateral displacement at deck level in *x*-direction
u_{xb}	Lateral displacement at base isolator level in *x*-direction
u_{xs}	Lateral displacement at deck level in *x*-direction
u_{y}	Lateral displacement at deck level in *y*-direction
u_{yb}	Lateral displacement at base isolator level in *y*-direction
u_{ys}	Lateral displacement at deck level in *y*-direction
u_{θ}	Torsional displacement at deck level
$u_{\theta\mathrm{b}}$	Torsional displacement at base isolator level
$u_{\theta\mathrm{s}}$	Torsional displacement at deck level
v_{s}	Shear wave velocity of the soil
x	Peak axial displacement of column or horizontal deck displacement in *x*-direction
x'	Increase in horizontal displacement with respect to straight column in *x*-direction
x'_{c}	Increase in horizontal displacement with respect to straight column at corner nodes in *x*-direction
x_{b}	Lateral displacement at base isolator level
x_{c}	Corner horizontal displacement in *x*-direction
x_{f}	Lateral displacement at foundation level
x_{i}	Distance of i^{th} column from center of mass in *x*-direction
x_{s}	Lateral displacement at deck level
y	Horizontal deck displacement in *y*-direction
y'	Increase in horizontal displacement with respect to straight column in *y*-direction

y'_{c}	Increase in horizontal displacement with respect to straight column at corner nodes in *y*-direction
y_{c}	Corner horizontal displacement in *y*-direction
y_{i}	Distance of i^{th} column from center of mass in *y*-direction
z	Peak transverse displacement of column or vertical deck displacement
z_1	Vertical displacement of deck slab or displacement in first degree of freedom
z_2	Vertical displacement of column or displacement in second degree of freedom
z_{m}	Vertical displacement at center of bearing
z'	Increase in vertical displacement
z'_{m}	Increase in vertical displacement with respect to straight column at middle of beam
α	Ratio of post to pre-yielding stiffness or percentage of initial bend with respect to column height
β	Dimensionless parameter used in Wen's model
β_0	Damping coefficient
δ	Column mid-height deflection
ξ	Material damping ratio
ξ_{b}	Critical damping ratio of isolation system
ξ_{s}	Critical damping ratio of superstructure
λ_{s}	Superstructure frequency ratio
λ_{n1}	Natural frequency ratio in first mode
λ_{n2}	Natural frequency ratio in second mode
υ	Poisson's ratio of the soil

ρ	Density of the soil
τ	Dimensionless parameter used in Wen's model
ϖ	Ratio between forcing frequency to the natural frequency
ϖ_0	Predominant frequency of loading
ϖ_{b}	Natural frequency of the base isolator
ϖ_{m}	Operating frequency of the rotary machine
ϖ_{n}	Natural frequency
ϖ_{n1}	Natural frequency in first mode
ϖ_{n2}	Natural frequency in second mode
ϖ_{xb}	Natural frequency of the of isolation system for torsionally uncoupled system in *x*-direction
ϖ_{xs}	Natural frequency of the torsionally uncoupled superstructure in *x*-direction
ϖ_{yb}	Natural frequency of the of isolation system for torsionally uncoupled system in *y*-direction
ϖ_{ys}	Natural frequency of the torsionally uncoupled superstructure in *y*-direction
$\varpi_{\theta\mathrm{s}}$	Torsional frequency of the torsionally uncoupled superstructure
$\varpi_{\theta\mathrm{b}}$	Torsional frequency of the isolator for torsionally uncoupled system
$\ddot{u}_{\mathrm{xb}}$	Lateral acceleration at base isolator level in *x*-direction
$\ddot{u}_{\mathrm{xg}}$	Earthquake ground acceleration in *x*-direction
$\ddot{u}_{\mathrm{xs}}$	Lateral acceleration at deck level in *x*-direction
$\ddot{u}_{\mathrm{y}}$	Deck lateral acceleration in *y*-direction
$\ddot{u}_{\mathrm{yb}}$	Lateral acceleration at base isolator level in *y*-direction
$\ddot{u}_{\mathrm{yg}}$	Earthquake ground acceleration in *y*-direction

$\ddot{u}_{\mathrm{ys}}$	Lateral acceleration at deck level in *y*-direction
$\ddot{u}_{\theta\mathrm{b}}$	Torsional acceleration at base isolator level
$\ddot{u}_{\theta\mathrm{s}}$	Torsional acceleration at deck level
$\ddot{x}_{\mathrm{b}}$	Lateral acceleration at base isolator level
$\ddot{x}_{\mathrm{f}}$	Lateral acceleration at foundation level
$\ddot{x}_{\mathrm{s}}$	Lateral acceleration at deck level
$\ddot{\theta}_{\mathrm{b}}$	Rotational acceleration at base isolator level
$\ddot{\theta}_{\mathrm{f}}$	Rotational acceleration at foundation level
$\ddot{\theta}_{\mathrm{s}}$	Rotational acceleration at deck level
$\dot{x}_{\mathrm{b}}$	Lateral velocity at base isolator level
$\dot{x}_{\mathrm{f}}$	Lateral velocity at foundation level
$\dot{x}_{\mathrm{s}}$	Lateral velocity at deck level
$\dot{Z}$	Non-dimensional hysteretic velocity
Δt	Time interval of input acceleration

ABBREVIATIONS

FEM	Finite Element Method
BEM	Boundary Element Method
FDM	Finite Difference Method
SDOF	Single degree of freedom
SSI	Soil-structure interaction
SSC	Soft soil creep
LNG	Liquified natural gas
LRB	Lead rubber bearing
N-Z	New-Zealand rubber bearing
RFBI	Resilient friction-based isolator
EDF	Electricite-de-France system
CM	Center of mass
CR	Center of rigidity
RC	Reinforced concrete
TG	Turbo-generator