EARTHQUAKE BASE ISOLATION OF SECONDARY SYSTEMS USING ELASTOMERIC AND SLIDING SYSTEMS

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by

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Submitted

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Dedicated to all nears and dears for their complete faith, encouragement and love.

CERTIFICATE

This is to certify that the thesis entitled, "**EARTHQUAKE BASE ISOLATION OF SECONDARY SYSTEMS USING ELASTOMERIC AND SLIDING SYSTEMS**" being submitted by **Mr. Pravin Shivaji JAGTAP** 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 my supervision for the submission of thesis, which to my 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 my knowledge and belief.

New Delhi
Monday, 11th May, 2020.

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ABSTRACT

In most industrial facilities, multi-storeyed structures, and nuclear power plants relatively lighter structures/ secondary systems (SS) are attached to the walls or housed on certain floors of the heavier structures/ primary structures (PS). Different types of failure of the SS are noticed during past earthquakes; namely, failure of the fire-frightening facilities, elastic buckling of liquid storage tank walls, failure of library book shelves, HVAC systems, chemical storage containers, connections failure of water supply pipes, etc. Safety of the SS is vital for proper functioning of the power plants, industrial facilities, hospitals, and other important structures under some catastrophic events of earthquakes. Failure of the SS may pose life hazards in addition to economical and building functioning loss. Seismic performance of the SS can be improved and those also can be safeguarded effectively from the disastrous effects of earthquake-borne vibrations by using the seismic base isolation technology. From the review of the literature, it is found that, base isolation in case of SS is not thoroughly investigated yet for its effectiveness in earthquake response reduction, despite from the overall effectiveness of the base isolation in protecting the PS. Most importantly, there is no investigation that clarifies upon the choice of isolation system and its dynamic parameters to be used for isolation of the SS installed in PS. In view of the unavailability of experimental data and lack of information on the dynamic performance of various types of base isolation systems used in practice, this research focuses on addressing these two issues first and furthers the efforts by investigating the base isolation used for SS. The aim of this research is to assess effectiveness of base isolation for use in protection of the SS housed within primary system under earthquakes. Moreover, investigating comparative performance of various types of base isolation systems, viz. (a) elastomeric bearings and (b) sliding systems is aimed. Based on the existing knowledge for manufacturing of the bridge bearings in India elastomeric and sliding bearings are designed, manufactured and characterized at laboratory. Stability analysis of the elastomeric bearings are conducted by developing its 3D finite element (FE) models in a commercially available software ABAQUS®. These bearings are currently manufactured and used in India; and, in this context, the present study is useful for the development of indigenous isolation systems and their implementations for safeguarding the SS.

Effect of the dynamic properties of the SS and their housing elevations (levels) within the PS on the response of both the multi-storied PS and SS are investigated experimentally

(shake table investigations) and numerically. Additionally, an experimental study, using shake-table, on base-isolated and non-isolated anchored SS is also conducted. In the current practice of seismic design of the PS or SS, interaction between the two is often ignored. This interaction effect is studied through the present investigations. Moreover, a mathematical model of a five-storied PS housing a single-storied SS at different floor elevations is developed and verified with experimental results.

Experimental investigations on response of the SS while housing them in two adjacent demonstration buildings at IIT Guwahati campus is set by developing a programme for real time event monitoring. A continuous real-time response monitoring of the instrumented SS setup using a computer-aided data-acquisition system helps in study of the SS response under real earthquake event. Furthermore, the response of SS is also studied while modelling them in two real-life RCC building one supported with the combination of elastomeric and sliding isolators and another supported on double concave friction pendulum bearing. The studies have showed the effectiveness of PS base-isolation for protecting the SS.

Deterministic and stochastic response study for piping type SS are further conducted and comparative assessment of response of piping type SS is made between fixed-base and base-isolated structures. The stochastic response of the base-isolated PS with SS and fixed-base PS with secondary system are computed in a polynomial chaos framework and the details of the stochastic framework are presented in details. The seismic response of the floor mounted liquid storage tank type SS with and without isolation system are further studied. A new isolation system for the light-weight SS is devised and proposed herein.

Based on the aforementioned comprehensive, FE, experimental, and numerical studies conducted on fixed-base and base-isolated SS it is observed and concluded that, in case of the SS equipments design forces should be calculated based on coupled analysis than cascading analysis. Floor response spectra govern the design of isolation systems for SS. The sliding isolators being highly nonlinear imparts more acceleration while moving from stick condition to slip condition. This type of behaviour is detrimental for the acceleration-sensitive type of the SS. The elastomeric isolators are the smooth-type systems; hence, the floor accelerations in this type of isolation system are less which is beneficial in safeguarding the acceleration-sensitive SS. Base-isolated PS helps in reducing its inter-story drift, which benefits to safeguard piping-type displacement-sensitive SS.

सार

अधिकांश औद्योगिक सुविधाएं, बहु-मंजिला संरचनाएं, और परमाणु ऊर्जा संयंत्रों में अपेक्षाकृत हल्की संरचनाएं / माध्यमिक प्रणाली (एसएस सिस्टम) ज्यादा करके दीवारों पर या भारी संरचनाओं / प्राथमिक संरचनाओं (पीएस) के कुछ मंजिलों पर रखे जाते हैं। पिछले भूकंपों के दौरान हल्की संरचनाओं (एसएस) की विभिन्न प्रकार की विफलताएं देखी गयी हैं; अर्थात्, अग्नि-भयावह सुविधाओं की विफलता, तरल भंडारण टैंक की दीवारों की लोचदार बकलिंग, पुस्तकालय की बुक अलमारियों की विफलता, एचवीएसी सिस्टम की विफलता, रासायनिक भंडारण कंटेनर की विफलता, पानी की आपूर्ति पाइप की कनेक्शन विफलता आदि। भूकंप की कुछ भयावह घटनाओं के तहत बिजली संयंत्रों, औद्योगिक सुविधाओं, अस्पतालों और अन्य महत्वपूर्ण संरचनाओं के समुचित कार्य के लिए एसएस की सुरक्षा महत्वपूर्ण है। एसएस की विफलता आर्थिक और इमारत के कामकाज के नुकसान के अलावा जीवन के लिए खतरा पैदा कर सकती है। एसएस के भूकंपीय प्रदर्शन में सुधार किया जा सकता है और भूकंपीय आधार (बेस) अलगाव (आइसोलेशन/ विलगता) प्रौद्योगिकी का उपयोग करके भूकंप-जनित कंपन के विनाशकारी प्रभावों से भी उन्हें प्रभावी ढंग से सुरक्षित किया जा सकता है। अभी तक के साहित्य की समीक्षा से यह पाया गया है कि, प्राथमिक संरचनाओं (पीएस) की रक्षा में आधार अलगाव तकनीक की समग्र प्रभावशीलता के बावजूद, भूकंप की प्रतिक्रिया में कमी करने के लिए आधार अलगाव की प्रभावशीलता एसएस के मामले में अभी तक पूरी तरह से जांची नहीं गई है। सबसे महत्वपूर्ण बात यह है कि, ऐसी कोई जांच नहीं है जो पीएस में स्थापित एसएस के अलगाव के लिए अलग-थलग प्रणाली और उसके गतिशील मापदंडों के विकल्प पर स्पष्ट करती है। प्रायोगिक डेटा की अनुपलब्धता और व्यवहार में उपयोग किए जाने वाले विभिन्न प्रकार के बेस आइसोलेशन सिस्टम के गतिशील प्रदर्शन पर जानकारी की कमी को देखते हुए, यह शोध पहले इन दो मुद्दों को संबोधित करने पर ध्यान केंद्रित

करता है और एसएस के लिए इस्तेमाल किए गए आधार अलगाव प्रणाली की जांच करके प्रयासों को विफल करता है। इस शोध का उद्देश्य भूकंप के तहत प्राथमिक प्रणाली के भीतर स्थित एसएस के संरक्षण में उपयोग के लिए आधार अलगाव की प्रभावशीलता का आकलन करना है। इसके अलावा, विभिन्न प्रकार के बेस आइसोलेशन सिस्टम के तुलनात्मक प्रदर्शन की जांच करना। (अ) इलास्टोमेरिक बियरिंग्स और (ब) स्लाइडिंग (सरकन) प्रणाली का उद्देश्य है। भारत में ब्रिज बियरिंग के निर्माण के लिए मौजूदा ज्ञान के आधार पर एलास्टोमेरिक और स्लाइडिंग बियरिंग को प्रयोगशाला में डिजाइन, निर्मित और विशेषता बनाया गया है। इलास्टोमेरिक बियरिंग्स का स्थिरता विश्लेषण व्यावसायिक रूप से उपलब्ध सॉफ़्टवेयर अबाकस में इसके त्रि-आयामी (३-डी) परिमित तत्व (फई) प्रतिमान (मॉडल) विकसित करके किया जाता है। ये बीयरिंग वर्तमान में भारत में निर्मित और उपयोग किए जाते हैं; और, इस संदर्भ में, वर्तमान अध्ययन स्वदेशी अलगाव प्रणालियों के विकास और एसएस की सुरक्षा के लिए उनके कार्यान्वयन के लिए उपयोगी है।

एसएस के गतिशील गुणों और उनके आवास उन्नयन (स्तरों) का प्रभाव बहु-मंजिला पीएस और एसएस दोनों की प्रतिक्रिया पर पीएस के भीतर प्रयोगात्मक रूप से (शेक टेबल जांच) और संख्यात्मक रूप से जांच की गई है। इसके अतिरिक्त, बेस-पृथक (बेस-) और गैर-पृथक लंगर एसएस पर शेक-टेबल का उपयोग करके एक प्रयोगात्मक अध्ययन भी आयोजित किया गया है। पीएस या एसएस के भूकंपीय डिजाइन के मौजूदा अभ्यास में, दोनों के बीच बातचीत को अक्सर अनदेखा किया जाता है। यह अंतःक्रियात्मक (इंटरेक्शन) प्रभाव वर्तमान जांच के माध्यम से अध्ययन किया गया है। इसके अलावा, पांच मंजिला पीएस आवास के एक गणितीय मॉडल को अलग-अलग मंजिल की ऊंचाई पर एकल-मंजिला एसएस विकसित और प्रयोगात्मक परिणामों के साथ सत्यापित किया गया है।

एसएस की प्रतिक्रिया पर प्रायोगिक जाँच, आई आई टी गुवाहाटी कैंपस में दो आसन्न (एड़जसेन्ट) प्रदर्शन भवनों में आवास करते हुए, रियल टाइम इवेंट मॉनिटरिंग के लिए एक कार्यक्रम विकसित करके निर्धारित किया गया है। कंप्यूटर-एडेड डेटा-अधिग्रहण प्रणाली का उपयोग करके इंस्ट्रूमेंटेड एसएस सेटअप की निरंतर वास्तविक समय की निगरानी वास्तविक भूकंप की घटना के तहत एसएस प्रतिक्रिया के अध्ययन में मदद करती है। इसके अलावा, रियल आरसीसी बिल्डिंग में भी एसएस की प्रतिक्रिया का अध्ययन किया गया है, जहा पर उन्हें दो वास्तविक रियल आरसीसी बिल्डिंग में मॉडलिंग करते हैं, जो इलास्टोमेरिक और स्लाइडिंग आइसोलेटर्स के संयोजन के साथ समर्थित है और दूसरा आरसीसी बिल्डिंग डबल अवतल घर्षण पेंडुलम असर पर समर्थित है। अध्ययनों ने एसएस की रक्षा के लिए पीएस आधार-अलगाव की प्रभावशीलता को दिखाया है।

पाइपिंग प्रकार एसएस के लिए नियतात्मक (डेटर्मीनिस्टिक) और स्टोकेस्टिक प्रतिक्रिया अध्ययन आगे आयोजित किए गए हैं और पाइपिंग प्रकार एसएस की प्रतिक्रिया का तुलनात्मक मूल्यांकन निश्चित-आधार और आधार-पृथक संरचनाओं के बीच किया गया है। एसएस के साथ बेस-पृथक पीएस और माध्यमिक प्रणाली के साथ फिक्स्ड-बेस पीएस की स्टोकेस्टिक प्रतिक्रिया को एक बहुपद अराजकता (पोलीनोमिअल चाओस) ढांचे में गणना की जाती है और स्टोकेस्टिक ढांचे के विवरण में विवरण प्रस्तुत किए जाते हैं। इसके अलावा, फर्श पर तरल भंडारण टैंक प्रकार के भूकंपीय प्रतिक्रिया एसएस के साथ और बिना अलगाव प्रणाली का अध्ययन भी किया गया है। लाइट-वेट एसएस के लिए एक नई अलगाव (आइसोलेशन) प्रणाली तैयार की गई है और यहां प्रस्तावित है।

पूर्व-आधार पर व्यापक, एफई, प्रयोगात्मक और संख्यात्मक-आधार पर किए गए अध्ययनों के आधार पर, फिक्स्ड-बेस और बेस-आइसोलेटेड एसएस का व्यवहार देखते हुए यह निष्कर्ष निकाला गया है कि एसएस उपकरणों के डिजाइन के मामले में कैस्केड विश्लेषण की तुलना में युग्मित विश्लेषण के आधार पर गणना की जानी चाहिए। तल प्रतिक्रिया स्पेक्ट्रा एसएस के

लिए अलगाव प्रणालियों के डिजाइन को नियंत्रित करती है। स्लाइडिंग आइसोलेटर्स अत्यधिक नॉनलाइनियर होने के कारण स्टिक कंडीशन से स्लिप कंडीशन की ओर बढ़ते हुए अधिक त्वरण प्रदान करता है। इस प्रकार का व्यवहार एसएस के त्वरण-संवेदनशील प्रकार के लिए हानिकारक है। इलास्टोमेरिक आइसोलेटर्स सुचारू प्रकार की प्रणाली (सिस्टम) हैं; इसलिए, इस तरह के अलगाव (आइसोलेशन) प्रणाली में मंजिल त्वरण (फ्लोर एक्सीलेरेशन) कम होते हैं जो त्वरण- प्रणाली (एक्सीलरेशन-सेंसिटिव) एसएस की सुरक्षा में फायदेमंद है। बेस-पृथक (बेस-आइसोलेटेड) पीएस अपने इंटर- मंजिला अभिप्राय (इंटर-स्टोरी ड्रिफ्ट) को कम करने में मदद करता है, जो पाइपिंग-प्रकार के विस्थापन-संवेदनशील एसएस को सुरक्षित करने के लिए लाभ देता है।

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NOTATIONS

$\ddot{x}_b(t)$	Acceleration at the isolation level
g	Acceleration due to gravity
x_g	Acceleration earthquake ground acceleration
$\{\ddot{x}_1\}$	Acceleration vector
Q	Characteristic strength
μ	Coefficient of friction in sliding systems
ξ^1	Collocation points
$[C]$	Damping matrix
$[C_T]$	Damping matrix of the total system comprising of primary structure and secondary system
ξ_s	Damping ratio of superstructure
D	Design (isolation) displacement
F^+	Force corresponding to Δ^+
F^-	Force corresponding to Δ^-
Δ^+	Maximum positive test displacement of isolator
Δ^-	Maximum negative test displacement of isolator
x_i	Deterministic coefficients - PC expansion
a_0, a_i, a_{ii}, a_{ij}	Deterministic coefficients in response surface method
$\{x_1\}$	Displacement vector
$x_p(t)$	Displacement vector of the primary structure (except the linked DOF)
$x_L(t)$	Displacement vector of the primary structure linked to the secondary system
$x_S(t)$	Displacement vector of the secondary system
ω_{eff}	Effective isolation frequency
T_{eff}	Effective isolation time-period
c_{eff}	Effective viscous damping constant
β_{eff}	Effective viscous damping of isolator for each cycle of loading
k_{eff}	Equivalent linear elastic stiffness for each cycle of loading of isolator (effective stiffness)
m_s	Floor mass of secondary system
m_p	Floor mass primary structure
Ω	Frequency of the earthquake excitation
F	Frictional force in sliding system
X	Input uncertain parameters
T_b	Isolation (bearing) time-period
ξ_b	Isolation damping ratio
ω_b	Isolation frequency
q	Isolator yield displacement
G	Limit state function
$[M]$	Mass matrix
$[M_T]$	Mass matrix of the total system comprising of primary structure and secondary system
m_b	Mass of base/ base-raft
D_M	Maximum displacement of bearing

μ_Y	Mean of y
Z	Non-dimensional hysteretic displacement component
N	Number of pc expansion terms
Ψ	Orthogonal basis
Y	Output uncertain parameter
ν	Poisson's ratio
k_b	Post-yield stiffness; linear elastic spring stiffness of isolator; isolation/ bearing stiffness; stiffness of isolated shear beam
P	Probability measure on sample space
ξ_1	Random variable
α	Ratio of post to pre-yield stiffness, isolation stiffness parameter
$\ddot{x}_b$	Relative acceleration of base mass
F_b	Restoring force developed in isolation systems
Ω	Sample space
G	Shear modulus
F	Sigma algebra
Σ	Standard deviation
σ_{nor}	Standard deviation of the underlying normal distribution
$[K]$	Stiffness matrix
$[K_T]$	Stiffness matrix of the total system comprising of primary structure and secondary system
K_p	Story stiffness primary structure
k_s	Story stiffness secondary system
t	Time duration
δt	Time interval for solving equations of motion
$x_T(t)$	Total displacement vector of the coupled system
M	Total mass of structure
W	Total weight of building
$\{r\}$	Vector of influence coefficients
$\{r\}$	Vector of influence coefficients
$\{\dot{x}_1\}$	Velocity vector
c_b	Viscous damping of bearing; isolation damping coefficient
β, τ, A and n	Wen's dimensionless hysteresis parameters
F_y	Yield strength of bearing

ABBREVIATIONS

2-D	Two-dimensional
3-D	Three-dimensional
AASHTO	American Association of State Highway and Transportation Officials
BI	Base-Isolated
BIPS	Base-Isolated Primary Structure
BISS	Base-Isolated Secondary System
C3D8H	Continuum 3 Dimensional Hybrid
C3D8R	Continuum 3 Dimensional Reduced Integration
CSB-A	Case Study Building-A
CSB-B	Case Study Building-B
DBE	Design Basis Earthquake
EDF	Electric de France System
FB	Fixed-Base
FBPS	Fixed-Base Primary Structure
FBSS	Fixed-Base Secondary System
F-D	Force Deformation
FE	Finite Element
FFT	Fast Fourier Transform
FPS	Friction Pendulum System
gPC	Generalised Polynomial Chaos
IBC	International Building Code
HDRB	High Damping Rubber Bearing
IS	Indian Standard
LRB	Laminated Rubber Bearing
LVDT	Linear Variable Displacement Transformer
MC	Monte Carlo
MCE	Maximum Capable Earthquake
MDOF	Multi-Degree-of-Freedom
MSSS	Multiply Supported Secondary System
N-Z	New-Zealand System
P-F	Pure-friction System
PGA	Peak Ground Acceleration
PS	Primary Structure
PSs	Primary Structures
PTFE	Poly-tetra-flouro-ethelene
QoI	Quantities of Interest
R-FBI	Resilient-friction Base Isolator
SDOF	Single-Degree-of-Freedom
SS	Secondary System
SSs	Secondary Systems
UBC	Uniform Building Code
DCFPS	Double Curvature Friction Pendulum System
RCC	Reinforced Cement Concrete