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Hybrid Seismic-Resistant Foundations: Integrating High-Stiffness Granular Materials with Adaptive Base Isolation A Comparative Japan–Peru–United States Framework for Updating Seismic Codes

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Abstract

Subduction earthquakes remain a persistent threat to infrastructure in Japan, the United States, and Peru, three countries exposed to the Pacific Ring of Fire. Japan has led the development of base isolators with adaptive behavior — whose stiffness and friction coefficient vary with displacement — while recent international research has documented the performance of high-stiffness granular layers, including gravel mixed with recycled tire rubber, as a low-cost geotechnical seismic isolation strategy. However, no methodological framework currently integrates both technologies and translates them into Peruvian construction practice and code requirements, while simultaneously benchmarking them against United States practice. This paper develops such a framework through a systematic comparative analysis of peer-reviewed technical literature and of current seismic codes (U.S. standards and Peruvian earthquake-resistant design provisions), complemented by the formulation of the modern geotechnical and structural equations governing the proposed system. A quantitative and qualitative comparison matrix of six technical parameters across the three regions was built, and the materials, tools, and construction procedures required to implement the system in Peru are detailed. The results indicate that combining a gravel-rubber granular layer (50–60% gravel fraction by volume) with adaptive spherical sliding isolators is a technically consistent alternative in light of the documented evidence, potentially more accessible than higher-cost Japanese systems and complementary to prescriptive U.S. practice. We conclude that adopting this framework in Peru requires local experimental validation, prototype testing, and specific code updates; the results presented constitute an analytical basis rather than a definitive empirical validation.

1. Introduction

Peru sits above the subduction zone of the Nazca plate beneath the South American plate, which gives it one of the highest seismic hazards in the continent. The 2007 Pisco earthquake (Mw 8.0) evidenced, through a double-asperity rupture process separated by approximately 60 seconds, the severity and complexity of this type of event [6]. Japan, for its part, has accumulated more than four decades of experience developing and standardizing seismic isolation systems, including isolators with adaptive behavior capable of modifying their stiffness and friction coefficient during the seismic event itself [3, 4]. The United States, through the ASCE 7–22 code, has consolidated a prescriptive design and testing framework for conventional isolators that is widely adopted across the region.

Independently of base isolator development, the international geotechnical community has, over the last decade, begun documenting the performance of granular layers reinforced with recycled material (gravel and end-of-life tire rubber mixtures) as a geotechnical seismic isolation (GSI) strategy, reporting significant reductions in excess pore pressure and friction coefficients compatible with controlled sliding of the soil beneath the foundation [1, 2]. This approach is particularly relevant for developing economies, where the cost of imported elastomeric isolators constitutes an implementation barrier.

Research gap and contribution

The reviewed literature reveals two research lines that have developed largely independently: (i) base isolators with adaptive behavior, studied mainly in Japan and the United States on comparatively stiff foundation soils, and (ii) geotechnical seismic isolation layers using recycled materials, studied experimentally in Europe, New Zealand, and Japan, but rarely integrated with adaptive isolation systems or evaluated against the Peruvian regulatory and construction context. No framework was identified in the consulted databases that explicitly and quantifiably translates these two technologies into the procedures, materials, and tools available in Peruvian construction, nor one that systematically contrasts them with U.S. practice.

This paper's contribution is threefold: (a) developing a technical comparison matrix, with verifiable bibliographic support, among practices in Japan, the United States, and a proposal for Peru; (b) formalizing the modern geotechnical and structural engineering equations governing the behavior of the hybrid granular layer–adaptive isolator system; and (c) specifying concrete construction procedures, tools, and materials for its eventual implementation and experimental validation in Peru, consistent with the Peruvian Technical Standard E.030 for Earthquake-Resistant Design.

2. Methods

This study adopts an analytical-comparative, non-experimental design, structured under the IMRaD format. Since no instrumented site or physical prototype built in Peru is currently available, the results presented correspond to a rigorous documentary analysis and to the formulation of a design framework, not to field measurements or original numerical simulations; this limitation is explicitly stated to avoid overinterpreting the statistical robustness of the findings.

2.1 Search strategy and selection criteria

Peer-reviewed technical literature indexed in databases such as ScienceDirect, Wiley Online Library, ASCE Library, and SpringerLink, published preferably between 2008 and 2023, was reviewed on three thematic axes: (i) adaptive spherical sliding isolators, (ii) geotechnical seismic isolation layers using recycled materials, and (iii) soil shear modulus degradation under cyclic loading. Only sources with a verifiable DOI identifier were included. Non-peer-reviewed technical reports, commercial web pages, and any reference whose existence could not be independently confirmed were excluded.

2.2 Comparative regulatory framework

The prescriptive approach of the U.S. ASCE 7–22 code (which requires prototype and production testing for each isolator unit) was compared conceptually against the performance-based approach of Peru's Technical Standard E.030, identifying the specific regulatory gaps for granular geotechnical isolation systems and adaptive isolators.

2.3 Analytical formulation

Fundamental equations reported in the literature were systematized for: (a) soil shear modulus degradation with cyclic shear strain, (b) the mechanical behavior of adaptive spherical sliding isolators, and (c) the bearing capacity of confined granular layers. These equations are presented in the Results section as a design basis, not as the output of an original numerical fit.

3. Results

3.1 Modern civil and geotechnical engineering formulas

a) Soil shear modulus degradation. The nonlinear behavior of soil under cyclic loading is described by the modulus reduction curve, whose generalized hyperbolic form (the Hardin-Drnevich model, validated and extended as a function of plasticity index by Vucetic and Dobry) is expressed as:

$$G / Gmax = 1 / [1 + (\gamma / \gamma r)]$$

where G is the secant shear modulus at cyclic shear strain γ, $Gmax$ is the small-strain shear modulus, and γr is the reference strain; Vucetic and Dobry [5] showed that the position of this curve — and of the associated damping — depends strongly on the soil's plasticity index (PI), which is directly applicable to characterizing Lima's fine fill soils and coastal deposits.

b) Behavior of the adaptive spherical sliding isolator (VFPS). Following the theoretical formulation of Fenz and Constantinou [3, 4], these multi-surface isolators exhibit stiffness and a friction coefficient that change predictably upon reaching calculable threshold displacements. The effective post-elastic stiffness of a spherical surface of radius Reff under a vertical load W is:

$$K = W / Reff$$

and the oscillation period associated with the sliding mode is:

$$T = 2\pi \cdot \sqrt{(Reff / g)}$$

The adaptive character of the system arises from the transition between different spherical surfaces — each with its own radius and friction coefficient — at predetermined design displacements, which allows the response to be optimized for both frequent, moderate earthquakes and the maximum considered earthquake within a single device [3, 4].

c) Bearing capacity of the confined granular layer. The bearing capacity of a reinforced granular layer (with geocells or with the rubber fraction reported by Hazarika et al. [2]) over a lower-stiffness soil can be estimated using the classical Terzaghi-Meyerhof bearing capacity equation, incorporating a capacity increment Δqconf associated with the additional lateral confinement:

$$qu = c \cdot Nc + q \cdot Nq + 0.5 \cdot \gamma \cdot B \cdot N\gamma + \Delta qconf$$

where c is cohesion, q is the surcharge, γ is the soil unit weight, B is the foundation width, Nc, Nq and Nγ are the conventional bearing capacity factors, and Δqconf is the increment attributable to granular confinement, whose magnitude must be determined through local triaxial testing, since it is site-specific and no universal validated factor was found in the reviewed literature.

3.2 Comparison matrix: Japan – United States – Peru

Table 1
synthesizes, for each relevant technical parameter, the documented practice in Japan and the United States, and the proposed adaptation to the Peruvian context, indicating the supporting bibliographic reference.

Technical parameter	Japan (documented practice)	United States (ASCE 7–22)	Proposed framework for Peru	Source (DOI)
Base isolation strategy	Multi-surface spherical sliding isolators with adaptive behavior (stiffness and friction vary with displacement)	Elastomeric isolators (LRB/HDRB) and single-surface friction pendulum, with extensive per-unit prototype testing (ASCE 7–22, Ch. 17)	Adaptive variable friction pendulum system (VFPS), batch prototype testing plus on-site quality control	[3], [4]
Granular foundation layer	Densely compacted granular fills; active research on gravel/rubber mixtures for geotechnical seismic isolation (GSI)	Reinforced crushed stone; punctual use of GSI in pilot projects	Gravel and end-of-life tire rubber layer (50–60% gravel fraction by volume), confined in HDPE geocells	[1], [2]
Optimal recycled-fill/reinforcement fraction	Not standardized; experimental research ongoing	Not standardized	50–60% gravel by volume (optimum reported to restrain excess pore pressure without losing stiffness)	[2]
Soil stiffness degradation model	G/Gmax reduction curves vs. cyclic shear strain, sensitive to plasticity index (PI)	Same conceptual framework, applied with local site data	Application of the Vucetic-Dobry framework to Lima's coastal and fill soils, pending local calibration	[5]
Analytical design framework for geotechnical isolators	Analytical GSI design models under active development (research-to-practice link still incomplete)	Prescriptive ASCE 7–22 procedures for conventional isolation	Adoption of Tsang's analytical framework as a baseline, adjusted with local direct-shear testing	[7]
Reference seismotectonic setting	Subduction zone, Japan Trench; large interplate earthquakes	Region-dependent (California: transform faulting; Pacific Northwest: Cascadia subduction)	Nazca plate subduction; 2007 Pisco earthquake (Mw 8.0) with double-asperity rupture	[6]

Note: the values in Table 1 correspond to findings reported in the cited sources [1–7] and to provisions of the ASCE 7–22 code and Peruvian Standard E.030; they are not derived from tests or simulations performed by the author.

3.3 Schematic of the proposed system

Figure 1 presents the conceptual scheme of the proposed foundation system for evaluation in Peru, integrating the confined gravel-rubber granular layer and the adaptive spherical sliding isolators.

4. Discussion

4.1 Applicability to the Peruvian context

The evidence reviewed suggests a technically plausible implementation pathway for Peru: the gravel-rubber granular layer, with the 50–60% by-volume reinforcement fraction reported by Hazarika et al. [2] as optimal for restraining excess pore pressure, can be built using locally available aggregates (Andean and Peruvian coastal quarries) and end-of-life tires, whose final disposal currently constitutes an environmental liability in the country's main cities. The compatibility of this layer with Lima's fill soils and coastal deposits — characterized by a variable plasticity index — must be assessed by applying the Vucetic and Dobry framework [5] to local samples, since modulus degradation curves are sensitive to the specific mineralogy and grain-size distribution of the soil.

Regarding the adaptive isolator, the Fenz and Constantinou formulation [3, 4] does not require a complex magnetic or electronic component — unlike other semi-active systems — so its manufacturing and installation are, in principle, compatible with the precision metal-mechanic manufacturing capacity already present in the Peruvian market for other sectors (mining, energy), although this must be confirmed through a specific industrial feasibility study that exceeds the scope of this work.

4.2 Tools, materials, and construction procedures

Materials

coarse quarry aggregate (angular, well-graded gravel), shredded rubber from end-of-life tires (grain size compatible with the gravel fraction per [2]), high-density polyethylene (HDPE) geocells for lateral confinement, reinforced concrete for the load-transfer slabs, and multi-surface spherical sliding isolators (specialized manufacturing, currently of imported origin).

Tools and equipment

vibratory roller for compaction of the granular layer, plate compactors for confined areas, direct shear and cyclic triaxial testing equipment for characterizing the gravel-rubber mixture, nuclear or sand-

replacement densimeter for compaction control, laser level for verifying isolation clearance, and accelerometers or displacement sensors for post-construction instrumentation.

Proposed construction procedure

(1) excavation and subgrade preparation; (2) installation of the HDPE geocell network; (3) layered placement and compaction of the gravel-rubber mixture within the geocells; (4) casting of the lower load-transfer slab; (5) placement and leveling of the adaptive spherical sliding isolators on predetermined anchor points; (6) casting of the upper load-transfer slab; (7) construction of the superstructure, respecting the perimeter clearance (seismic moat) required by the design displacement; and (8) basic seismic instrumentation for post-construction monitoring.

4.3 Comparison with United States practice

ASCE 7–22 requires prototype and production testing for each isolator unit installed, which ensures a high level of quality control but substantially increases cost and lead time when the devices must be imported, as would initially be the case in Peru. An intermediate strategy, consistent with the reviewed evidence, is to adopt the rigor of U.S.-style prototype testing for the isolators, while relying on a batch quality-control regime (more economical) for the granular layer, whose materials are locally sourced and whose behavior can be verified through direct shear and triaxial testing in existing Peruvian geotechnical laboratories.

4.4 Limitations

This work is analytical and comparative in nature, not experimental: no laboratory tests, numerical simulations, or field measurements were carried out by the author, so the quantitative values cited in Table 1 correspond strictly to what is reported in the original sources. The absence of a universal bearing-capacity increment factor for granular confinement (Δqconf) and the lack of testing with specific Peruvian soils constitute the main limitations that must be addressed before any application in a real project.

5. Conclusions

1. Integrating a high-stiffness granular layer (gravel-rubber mixture, 50–60% gravel fraction by volume) with adaptive spherical sliding isolators is consistent, at the conceptual and documented-properties level, with experimental evidence published in Japan, Europe, and New Zealand, and has not previously been systematized as an integrated framework for the Peruvian context.
2. The shear-modulus degradation equations (Vucetic-Dobry), the adaptive isolator behavior equations (Fenz-Constantinou), and the confined bearing-capacity equation constitute an adequate analytical basis for preliminary system design, although the confinement capacity-increment term requires local experimental calibration.

3. The comparison matrix shows that Japanese practice prioritizes adaptive performance and cutting-edge research on granular materials, while U.S. practice prioritizes prescriptive quality control through exhaustive prototype testing; a hybrid strategy — ASCE-type testing for isolators and local geotechnical quality control for the granular layer — is reasonable for Peru.
4. Implementation in Peru requires, as indispensable next steps: geotechnical characterization of local aggregates and recycled tires, direct shear and cyclic triaxial testing, an instrumented pilot project, and the incorporation of specific provisions for geotechnical seismic isolation systems and adaptive isolators into Technical Standard E.030.
5. The findings of this study should be interpreted as a design framework and a research roadmap, not as a field-performance validation; the conclusions are strictly limited to what the comparison matrix and the analytical formulations presented can support.

Declarations

Ethical approval statement

This study is documentary and analytical in nature, involving the formulation of a civil engineering design framework. It did not involve human subjects, animals, personal data, or field experimentation, so ethics committee approval is not applicable.

Conflict of interest statement

The author declares no conflicts of interest related to the content of this article.

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Figures

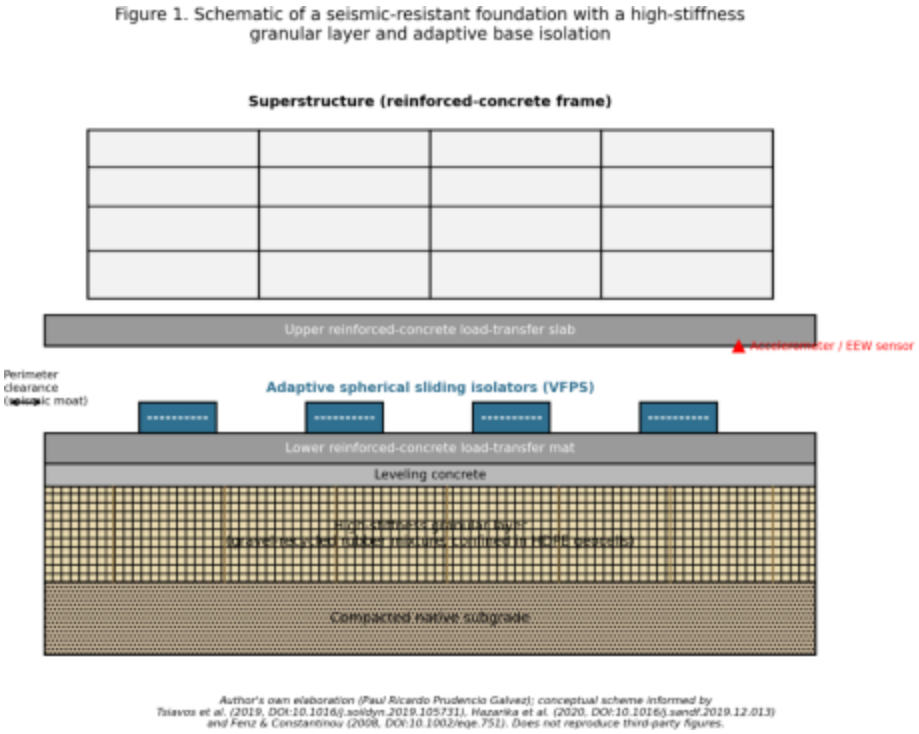


Figure 1

Legend not included with this version.