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Highways Construction Review in Seismic Hazard Zone

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Abstract: Roads have undergone significant evolution throughout history, with unquestionable economic and consequent social development. Various trends are currently emerging in their construction, without ignoring the fact that, during their useful life, these structures are subject to processes and phenomena that limit their safety and durability. Cuba, due to its geographic location, is influenced by significant seismic activity, the induced threats of which can have a significant negative impact on roads. This research proposes considerations for the execution of these linear works in the face of geological disasters, considering threats such as earthquakes, soil liquefaction, and landslides. The main results of this work are supported by a bibliographic review and documentary analysis of international experiences.

Key words: highways construction; seismic hazard; highways

1. Introduction

Road construction techniques have been emerging in Cuba for several decades. Numerous examples illustrate this, notably the construction of the Central Highway, which dates back more than 50 years. This structure is still in service as a result of the repair or reconstruction work that has been carried out.

One of the main aggravating factors for a road network is the occurrence of natural disasters, which are on the rise globally. The entire planet is frequently hit by some type of disaster, with varying degrees of severity. Among these, earthquakes constitute one of the worst threats (Figure 1a-b).

a) Earthquake in Honduras.

b) Effect of liquefaction on roads.

Figure 1. Impact of earthquakes on roads in recent years.

Due to its geographical location, Cuba has geological, tectonic and topographic characteristics that make it vulnerable to disasters of geological origin in much of its territory (Figure 2 a-b).

a) Damage caused in the La Alameda area.

b) Landslide that compromises the road network.

Figure 2. Impact of earthquakes on roads in Cuba.

The province of Santiago de Cuba is located on the Cuban microplate, at the southern boundary of the North American Plate and the northern boundary of the Caribbean Plate. This area is characterized by the type of seismic activity known as interplate seismic activity, linked to the Bartlett-Caimán structure (eastern seismogenic zone), which is characterized by an open transform fault system with a graben at its center (Bartlett Trench) (Figure 3).

Figure 3. Tectonic plates adjacent to the plate on which the Cuban archipelago is located.

Cuban seismological research places Santiago de Cuba as the area with the greatest seismic risk in the country. More than 60% of the perceptible and strong earthquakes reported in the country have had their epicenter in this province. These have been recorded in the area between the towns of Chivirico and Baconao, shaken by more than 1,000 perceptible earthquakes since 1528.

The effect of this threat on structural works has been studied in depth; However, there are currently significant gaps in roadworks, considering that earthquakes can induce or trigger other highly destructive geological hazards, such as surface failure or opening of material on the Earth's surface in the form of gigantic cracks, failures in natural or artificial slopes due to ground shaking in unstable areas or with relatively steep topography, liquefaction of unconsolidated material due to ground shaking, subsidence or depression of the ground surface as a result of the settling of soft sediments, and so-called tsunamis, generated by underwater seismic activity (National Center for Seismological Research (Cenais), 2010). All of these have a significant impact on roads.

Therefore, there are certain uncertainties in the behavior of roads under the action of earthquakes and other induced hazards, often caused by inadequate road design solutions and generally responsible for limiting their durability and safety.

This research delves into the topic to propose considerations for highway construction as an alternative for risk reduction. The negative impact of geological disasters on these linear works was taken into account, based on a literature review and international experiences with strong earthquakes in the region.

This experience draws attention to the fact that earthquake-related damage to all types of structures has a high failure rate as a result of unfavorable soil behavior and the low quality of some materials, in addition to inadequate quality control. Added to this are certain inconsistencies in road planning. These unfavorable behaviors tend to amplify the harmful consequences of earthquakes on roads, which is why attention should be drawn to highway construction in areas of high seismic risk.

2. Method

Based on documentary analysis, an exhaustive bibliographic review, and international experience, a characterization of road construction in high seismic hazard zones is carried out. Initially, the development of road networks and their influence on human progress are assessed, both from a social and economic perspective. The different trends in road construction currently documented in the specialized literature are also identified. Then, the seismic activity in Cuba is characterized, with emphasis on the southeastern region of the island. The impacts of earthquakes on these linear structures are identified; induced hazards are also referred to.

The stages and activities for road construction are identified. Each stage determines the considerations for construction to prevent disasters. As a good construction practice, long-term profitability is sought by preventing failures, eliminating repair needs, and reducing the impact of disasters.

3. Results

Road construction requires the creation of a continuous surface that crosses geographical obstacles and adopts a sufficient slope to allow for the circulation of vehicles and pedestrians. This process ranges from the removal of topsoil for the construction of the grade to the placement of traffic signals. Understanding the stages and activities during the construction process is essential, allowing for an assessment of the impact of geological hazards on each stage.

The stages into which the different activities of the road construction process can be grouped are defined as follows: Stage 1, called preliminary, includes preliminary and final layout, clearing, and debarking. Stage 2, construction of drainage works, includes excavation, channel clearance, base slab construction, underpinning, walls, and slabs, pipe and caisson placement, and joint sealing; as well as manual and mechanized re-swelling. The third stage, called earthwork, includes excavation of the grade and ditches, paving, leveling, wetting, and compaction of the soil material. Paving, as Stage 5, consists of subgrade preparation, subbase and base construction, primer spraying, and surface placement. Finally, Stage 6 of completion included the placement of signage and fencing devices.

The tables below summarize the proposed considerations by stage. (Table 1-2-3-4-5)

Table 1. Stage I (Preliminary)

Stage I (Preliminary)				
Activities	Preliminary layout	Land clearing	Debarking or removal of topsoil caps	Final layout
Description	Layout of inflection angles. Layout of the track centerline, both straight and curved. Layout and marking of factory centerlines.	Clearing the site's fall plan. Clearing and removing tree stumps. Buildings that need to be	Storage of topsoil in ridges located on both sides of the tracks. Excavation and transverse transfer of topsoil (on both sides	Redesign the road centerline. Restrict the embankment and clear the land.

Stage I (Preliminary)				
	Review and placement of fixed elevation points (FEPs)	demolished. Relocating communication lines (gas, electricity, etc.)	of the tracks and in continuous ridges).	
Suitable Considerations in Earthquake Zones				
A survey of the road or site is necessary to identify topographic features such as drainage, clearances, and slopes, as well as to add a certain level of geometric control to the project. A key link between design and construction is the use of standardized plans and drawings that show how the project should look, as well as specifications that describe how the work is to be done. The most appropriate method for staking out would be to determine all distances and elevations directly on the ground, supported by surveys to obtain the position of a point. Apply the best and most appropriate technologies available, such as GPS (Global Positioning System) and personal computer programs that allow for a high degree of accuracy in difficult terrain or for high-specification roads. Wood waste, tree tops and trunks, and stumps must be removed from the right-of-way at the foot of the fill slope before excavating for erosion control.				

Table 2. Stage II (Construction of Transversal Drainage Works. (Culverizers)

Stage II (Construction of Transversal Drainage Works. (Culverizers)					
Activities	Excavation	Cause cleaning	Construction of the base slab, support slab, walls, and fins	Laying pipes, caissons, and sealing joints	Manual or mechanized refilling
Description	Earth Material Soft rock	Cause cleaning	Formwork Placement of steel Concreting	Place the pipes or caissons on the base slab or prepared floor and then seal the joint	Plugging the pipes with the necessary material until reaching the subgrade
Appropriate Considerations in a Seismic Zone					
1) Zones of danger from liquefaction, subsidence, landslides, or fault rupture should be avoided. If the culvert is not located in one of these zones, then damage due to permanent ground deformation is unlikely. 2) In seismic zones, structural damage is not significant in small culverts of 1 m or less diameter, regardless of type. 3) The damaging effect of ground collapse on culverts increases with the size and length of the culvert. 4) If the culvert diameter is between 1.0 m and 2.0 m and the culvert is constructed from corrugated metal pipe, plastic-walled pipe, or reinforced concrete, the culvert has good seismic performance. 5) By using stable filling materials around culverts, it is possible to resist local buckling of thin-walled parts and fatigue of pavement parts under shallow coverage and heavy live load conditions. 6) Both the size of the stable material casing and its method and quality of placement are factors that affect the successful performance of flexible culverts. 7) Circular cross-sections are more resistant. 8) The type of culvert can contribute to its failure during a seismic event. In this case, there are two main groups of culverts: flexible ones composed of metallic or thermoplastic materials, and rigid ones made of reinforced concrete, unreinforced concrete, or masonry. 9) Materials such as plastic or reinforced concrete, ductile ones like metal, perform better than unreinforced or brittle materials. 10) Due to their fragility, unreinforced concrete culverts are not recommended for use in seismic regions. 11) Material efficiency is achieved by optimizing wall thickness, concrete strength, and, in the case of reinforced concrete, the placement and amount of reinforcing steel. 12) Under moderate to severe liquefaction, flexible open-wall culverts are more susceptible to drooping or cross-section collapse than rigid culverts. 13) For seismic zones, the design of rigid hinges should be avoided. 14) For embankment depths greater than 1.0 m, significant penetrations occur. Therefore, if the embankment saturation is less than 1.0 m, penetration is not a significant hazard. 15) From a seismic performance perspective, flexible culverts are resistant because they are very ductile and resist forces.					

Table 3. Stage III (Earth Movements and Filling)

Stage III (Earth Movements and Filling)							
Activities	Excavation	Excavation for drainage system (gutters, channels, etc.)	Transverse or longitudinal compensation	Extended (excavation or quarry material)	Leveling	Humidification	Compaction
Description	Unclassified excavation Unclassified waste Unclassified borrow excavation Sub-excavation Rock cuttings		Loading of material Hauling of material Unloading of material				
Appropriate Considerations in a Seismic Zone							
1) Identify areas underlying thick, poorly compacted embankments or loose foundation soils to prevent seismic compaction. 2) Avoid poorly compacted embankment materials or foundation materials susceptible to displacement. 3) Construct fills with an embankment slope ratio of 1-1/2" (horizontal to vertical) or steeper. In most soils, an embankment slope of 2:1 or steeper will promote vegetation growth. In tropical soils with high clay content within highly rainfed areas, an embankment slope of 3:1 is recommended. 4) The foundation materials most susceptible to seismic compaction are granular sediments. 5) Remove soft or poor soil and replace it with high-quality soil or rock material. 6) Materials most susceptible to earthquake-induced landslides include weakly cemented, weathered, or intensely fractured rocks, harder rocks where the predominant discontinuities descend from the slopes, loose unsaturated sands, saturated soils containing layers of sand and gravel alternating with sensitive clay, and uncompacted or poorly compacted man-made fills containing little clay layer. 7) Materials in the cut section are usually stiffer and less compressible than the material in the fill. Contact between cut and fill can impede the maneuverability of compaction equipment, leaving a poorly compacted section. 8) When subsoil conditions are uniform, settlements are likely to be fairly uniform and not detrimental. 9) Avoid relative compaction below 90% in embankments. 10) Improve foundation drainage and increase strength and resistance to liquefaction with the use of geogrids and geotextiles. 11) Add berms to embankments to improve slope stability.							

Table 4. Stage IV (Pavement)

Stage IV (Pavement)					
Activities	Subgrade preparation in Ca50 if necessary	Construction of base and sub-base (quarry material)	Primer Irrigation (only for bases)	Surface construction	
				Flexible pavement	Rigid pavement
Description		Quarry excavation Material transportation Material spreading Leveling Wetting Compaction		Surface cleaning (dust, mud, trash, water, etc.) Light irrigation (asphalt emulsion) Extension of the asphalt concrete Compaction (initial, intermediate, and final)	Shuttering Steel placement (joint elements) Concreting Curing Finishing
Appropriate Considerations in a Seismic Zone					
1) The structural responses of a pavement (stresses, displacements, and cracking) are significantly affected by the subgrade, and a large percentage of deflections can be attributed to it. 2) The required properties of the subgrade include strength, drainage, easy compaction, compaction retention, and volumetric stability. 3) Volumetric stability problems of subgrades are related to liquefiable soils (under dynamic loads), expansive soils, and collapsible soils. 4) Avoid placing pavements on embankments thicker than one or two meters, or loose natural materials such as collapsible soils or deposits of late Holocene sand, silt, or gravel.					

5) Subgrade treatment can be achieved by replacing or shifting the subgrade, stabilizing it with chemical agents, or using inserts (rock fragments, slabs). Pilings (timber, concrete, gravel, lime), palisades, geogrids, and geotextiles through preloading and drainage. 6) Where large differential settlements have occurred across narrow zones, rigid and flexible pavements have fractured and separated. 7) Shear and fill contact can cause displacement between rigid pavement slabs. 8) Pavement sections susceptible to seismic compaction are areas underlying thick, poorly compacted embankments or loose foundation soils.

Table 5. Stage Off (Termination)

Stage Off (Termination)		
Activities	Placement of vertical and horizontal signs	Construction of defense devices
Description		
Appropriate Considerations in a Seismic Zone		
1) Signs must be placed in areas where potential hazards such as landslides may occur. 2) Traffic sign posts must be buried at least 0.50 m, for which an excavation of at least 0.30 × 0.30 × 0.50 m must be made, while the space between the walls of the excavation and the base of the post must be filled with well-compacted concrete for improved pavement. 3) Construct barriers, which can be wooden structures, pre-cast reinforced concrete, pre-stressed concrete, or metal, consisting of posts and rails, placed along the sides of the road. 4) The distance from the ground surface to the bottom of the beam must not exceed 0.45 m. 5) Rail joints must be made in such a way that they do not have protrusions pointing away from traffic and, at the same time, provide the rail with sufficient structural continuity and rigidity.		

The Cuban archipelago, especially the southeastern part of the island, is highly seismic risk. This requires earthquake-resistant criteria not only in road design but also in construction. In Cuba, the greatest negative effects of an earthquake on roads are not only due to ground accelerations, but also to soil liquefaction and mass movements.

Geological disasters in road works, more than in design, have a marked impact on construction or execution, primarily in relation to the quality of materials and deficiencies in road planning and quality control during execution. Currently, road construction is carried out with innovative materials and technologies worldwide; among these, the use of additives and GPS, among others, stand out, which allow for improved quality in the execution of road works.

Due to economic considerations, terrain characteristics, and project objectives, roadways must meet the following requirements: their layout must be as direct as possible between the end points to be connected, and they must comply with all engineering principles and standards that allow for a roadway structure that is resistant, safe, durable, functional, economical, and pleasing to the driver's eye.

Proper planning requires avoiding problematic areas, such as locating roads in high-risk geological hazard zones, such as landslides, rockfalls, steep slopes (more than 60-70%), flooded or unstable areas, saturated soils, etc.; maintaining an adequate distance or separation from streams; and minimizing the number of drainage crossings and the number of connections between roads and waterways (Keller and Sherar).

The construction of the grade is the most important construction process in road construction, as it forms the body of the road. Correct soil assessment, moisture content, the required compaction on site, and ensuring the drainage of surface and groundwater, among other factors, are crucial for achieving adequate road strength and stability.

Roads must be constructed to quickly displace water away from the road surface to keep the surface drained without compromising its integrity.

Culverts comprise a diverse group of products with wide variations in material availability, properties, geometric wall sections, sizes, and shapes. Culverts are generally divided into two main classes: flexible and rigid. Flexible culverts are typically composed of metallic or thermoplastic materials and respond to loads differently than rigid culverts. Rigid culverts are not as dependent on soil support as flexible culverts. The latter can distort or collapse due to the loss of support provided by the surrounding soil. This, in turn, can lead to embankment loss and damage to the road surface, which is a threat to human life (Power, Fishman, Richards, Makdisi, Musser, & Youd, 2004).

Pavement damage has occurred in most major earthquakes. However, permanent soil deformation or ground failure has generally been the direct cause of the damage. In some cases, pavement disruption has occurred due to very intense ground movements, which locally uplift sections of the pavement. The structural responses of a pavement (stresses, displacements, and cracking) depend significantly on the subgrade. Required subgrade properties include strength, drainage, easy compaction, and volumetric stability.

Subgrade volumetric stability problems are related to liquefiable (under dynamic loads), expansive, and collapsible soils. Soils with these characteristics can be removed and replaced, as they are difficult to treat (Power et al. 2004). It is very important to know the type of material with which the pavement will be worked, as this is used to select the type of machinery and sufficient personnel to perform the work appropriately.

Special attention will be paid to the construction of longitudinal or transverse joints, whether cold or hot.

4. Conclusions

(1) Proper planning and construction of the road system are essential for community development and the flow of goods and services between communities.

(2) This research highlights the negative impact of earthquakes on roads, with damage being most severe to the superstructure, while also potentially affecting the substructure and surrounding area.

(3) It is very important from the outset to locate roads on stable terrain, on moderate slopes, in dry areas away from drainage, and isolated from other complex and difficult-to-access areas, to reduce vulnerability to seismic events and reduce maintenance and repair costs.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Centro Nacional de Investigaciones Sismológica (Cenais). (2010). Tabloide de Universidad para Todos Curso Elemental de Sismología. La Habana.

[2] Keller, G. y Sherar, J. (2001). Ingeniería de caminos rurales. Guía de Campo para las Mejores Prácticas de Administración de Caminos Rurales. México: Instituto Mexicano del Transporte.

[3] Power, M., Fishman, K., Richards, R., Makdisi, F., Musser, S., & Youd, T. L. (2004). Seismic Retrofitting Manual for Highway Structures: Part 2 - Retaining Structures, Slope, Tunnels, Culverts and Roadways. Federal Highway Administration.