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# A case for elevating coastal roads based on experiences from Hurricane Katrina and the Tohoku Tsunami

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## Abstract

Experiences from Hurricane Katrina and the Tohoku Tsunami illustrate that elevated coastal roads and railroads can be effective countermeasures to coastal flood inundation and damage. In Mississippi, a railroad embankment was reported to have limited the extent of inundation, while an at-grade coastal highway did not. In Tohoku, Japan, elevated coastal highways strongly reduced the extent of the inundation zone. A simple analysis shows that the additional expenditure required to elevate the coastal highway in Mississippi is only a few percent of the value of insured damages caused in the state by Hurricane Katrina, illustrating the economic benefit of elevating coastal roads as multifunctional flood defenses.

### Keywords

Tohoku Japan Tsunami, Hurricane Katrina, multifunctional flood defenses

## 1 Introduction

The coastal plains of Mississippi and Tohoku, Japan were both exposed to high-energy inundation events during Hurricane Katrina and the 2011 Tohoku Tsunami, respectively. In Mississippi, a low railroad embankment and at-grade highways were the only large infrastructure in the way of the storm surge. In Tohoku, however, roads and railroads along the coast were elevated (Suppasri et al., 2016), essentially multifunctional flood defenses (Tsimopoulou et al., 2012). Such multifunctional flood defenses have not been implemented in the US, but could be an economic means for coastal flood risk reduction. Multiple studies of multifunctional flood defenses in the Netherlands show their economic value and societal acceptance (Kok et al., 2013; van Loon-Steensma et al., 2014; Voorendt et al., 2015), though the latter can strongly vary with regional culture (Rittelmeyer, 2020). Here we compare the unprotected Mississippi coastline impacted by Hurricane Katrina in 2005, with the protected Sendai Plain impacted by the 2011 Tohoku tsunami.

## 2 Methodology

Photographs taken by the author, as well as a desktop review of published reports and the FEMA National Flood Hazard Layer (FEMA, 2025, which is a GIS environment for FEMA Flood Insurance Rate Maps), are used to evaluate the effect of an at-grade highway and an elevated railway embankment on damage to coastal Mississippi during Hurricane Katrina. News and municipal reports are used to understand the effect of elevated roads on reducing the extent of inundation in Miyagi and Fukushima Prefectures during the 2011 Tohoku, Japan tsunami. Generalized cost of levee construction is then applied for a simple estimate of the added cost to elevate Mississippi's coastal highway, and this cost is compared to insured damages from Hurricane Katrina in Mississippi.

Unlike the city of New Orleans to the west, the coast of Mississippi primarily consists of natural sandy beaches without engineered flood defenses. Port facilities in Gulfport and Biloxi (Figure 1) have bulkhead quay walls, but these are not elevated enough to prevent flooding from storm surge (Figure 2). Bulkhead walls also exist in some locations along the inland lagoons of St. Louis Bay and Biloxi Bay, along with intertidal wetland areas within these sheltered bays. However, a majority of the state's coastline facing the Gulf of Mexico is exposed sandy beach. These beaches are important for Mississippi's economy, and in some locations are maintained via nourishment programs. Since this study focuses on the state's long, seaward-facing exposed coastline, the limited locations with bulkheads or quay walls are not considered in the analysis.

## 3 Results

In Mississippi, Hurricane Katrina caused storm surge incident on low-lying coastal topography, upon which the coastal highway (US-90) and freeway further inland (I-10) are constructed at-grade for most of their lengths. Parallel to US-90 are the privately-owned CSX railroad tracks, which run seaward of US-90 west of Bay St. Louis, Mississippi, landward of US-90 between Pass Christian, Mississippi and Biloxi, Mississippi, and again seaward of US-90 between Biloxi, Mississippi and Mobile, Alabama (Figure 1). While the at-grade road infrastructure was not reported to have affected the extent of inundation, the CSX railroad embankment, though severely damaged (Sohrabi et al., 2023), was also reported to have contained the worst damage to its seaward side (Lasley et al., 2007; Simpson et al., 2010). Figure 2 shows the FEMA FIRM for Long Beach, Mississippi and Gulfport, Mississippi, where US-90 runs directly along the shoreline, and the CSX tracks are about 500 m inland. The FIRM shows that along most of this coast, US-90 does not affect the inundation area, while the CSX track embankment effectively functions to limit the inland extent of inundation. Figures 3 to 6 show photographs from coastal Mississippi at 1 month and 8 months after Hurricane Katrina hit. These show that the CSX railroad tracks functioned to partially impede the storm surge, as evidenced by the debris and vehicles caught on the embankment, despite the significant damage the embankment experienced. This contrasts with the at-grade highway and other roads, which neither caught debris nor apparently impeded flow, but also experienced significant damage (Figure 7).

In contrast with coastal Mississippi during Hurricane Katrina, transport infrastructure in northeast Japan (Tohoku) had a strong effect on confining inundation. Figures 8 and 9 respectively show examples of a highway and a freeway, each located about 2 km inland from the coast, during the tsunami event. Each of these roads is built on an embankment with underpasses for at-grade crossings. Even though the tsunami flooded through the underpasses, the total volume of floodwater flowing inland of these embankments was attenuated substantially compared to what it would have been if the embankments had not been present. Even though not designed as a flood defense, road embankments were so effective at limiting the extent of inundation during the 2011 Tohoku tsunami, that they have become recognized as multifunctional structures in the region, both for their primary role as transport arteries, and for their secondary role in flood defense. Figure 10 shows the current tsunami evacuation map for Sendai city. This illustrates the effect of the coastal prefectural highway No. 10 (Shiogama-Watari Road) embankment being responsible for containing the Level 1 (return period of decades to a century) event for most of the city, except on the northern sector of the map, where the national freeway No. 6 (Sendai Tobu Road) serves this role. In the central sector of the map, the national freeway serves to confine the Level 2 tsunami (return period of multiple centuries). This coastal prefectural highway embankment was raised approximately 6 m above foundation level after the 2011 event in order to serve officially as a flood defense, while the national freeway remains so only in a de facto manner. In addition to elevation on fill, for the coastal highway to serve as an official flood defense it was also reconstructed without underpasses, where such cross-highway access has been replaced by ramps on fill leading to signaled intersections. Other than this, the fill was designed as for a standard highway, with grass-armored slopes and an asphalt road at the crest (Sendai City, 2020). This contrasts with Japan's coastal dikes (often called seawalls) where crest, slope, and toe/heel are armored with heavy concrete in order to be "nebaritsuyoi", meaning resilient against the forces generated by tsunami impact (Suppasri et al., 2016).

Though elevated embankments for the purpose of flood control were not present in Mississippi during Hurricane Katrina, it is possible to estimate how much an elevated coastal road would cost, and compare that cost to the direct and indirect damages reported from Hurricane Katrina. The length of US-90 along the Mississippi coast is approximately 130 km. At 2 lanes, with each lane 12 ft wide, and assuming an embankment of 1:3 (V:H) slope and 10 ft height, this corresponds to an embankment profile area of 540 $ft^2$, or 50 $m^2$, and a total volume of $6.5 \times 10^6$ $m^3$. This embankment height of 10 ft built atop the natural ground level of 10 ft NAVD at the location of US-90, leads to a crest level of 20 ft NAVD, which is a spatial average of the maximum storm surge height that the Mississippi coast was exposed to (Dietrich et al., 2010). The unit cost of embankment construction can vary, depending especially on whether suitable material is available locally or needs to be trucked in, but is estimated at a median of \$30/$m^3$ to account for a range of ground conditions (NLSP, 2023). This leads to a total embankment construction cost of \$195 million. Assuming drainage culverts are required one per kilometer with a length of 84 ft to cross the base of the embankment, with a unit cost for a 36 inch culvert of \$60/foot (USFS, 2020) plus \$200 per each headwall (CDGRS, 2015), this leads to a total cost for culvert installation of \$700,000. The total embankment cost (including culverts) then becomes approximately \$196 million. This number excludes the cost of the asphalt road itself, along with its base and sub-base course, or any traffic detours or temporary structure needed for traffic continuity, thereby assuming these costs would need to be expended in any case during periodic maintenance and reconstruction. Compare this \$196 million cost to raise the road with the \$13.6 billion (2005 dollars) insured losses reported for Mississippi from Hurricane Katrina (Insurance Information Institute, 2010). These insured losses equal \$22.7 billion in 2025 dollars (US Bureau of Labor Statistics). The cost of elevating the road on fill would be less than 1% of these insured losses. Elsner et al. (2006) estimate the return period of a storm like Hurricane Katrina to be 21 years along the Gulf Coast as a whole, indicating that a multifunctional flood defense such as an elevated coastal highway would make for a practical countermeasure to damage, as the resulting expected annual damage (EAD) of \$1.1 billion per year alone is almost an order of magnitude greater than the cost to raise the coastal highway by 10 ft. Over an approximated 50-year design lifetime for the embankment, and applying the USACE FY2025 suggested discount rate of 3% (USACE, 2024), this EAD leads to a net present value of \$28 billion in damages avoided, more than 2 orders of magnitude greater than the construction cost of the embankment. However, it is important to note that this value includes damages from both storm surge and wind, and represents the whole state, so an additional county-specific, flood-damage-only analysis is carried out in the Discussion section below.

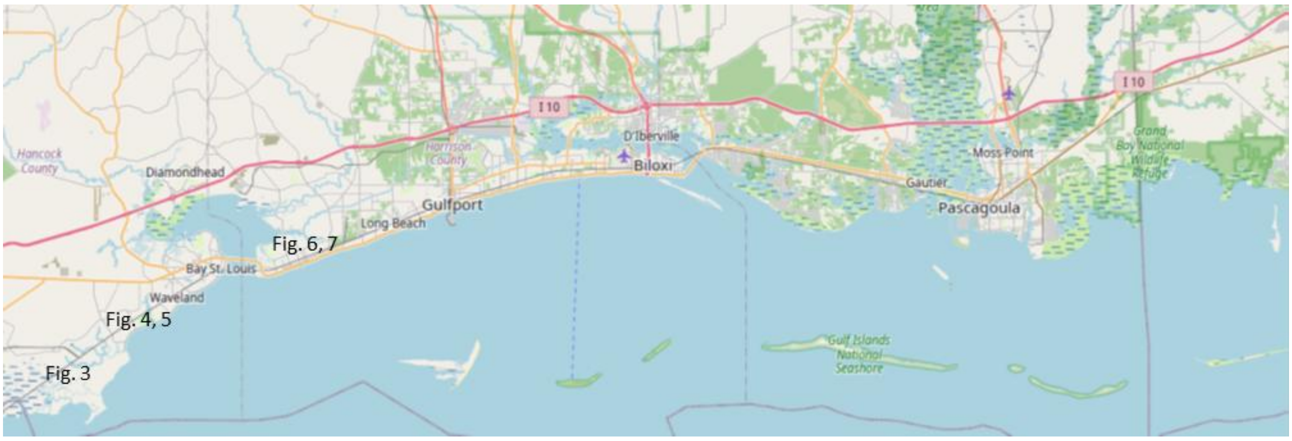


Figure 1. Map of Mississippi coastline (OpenStreetMaps, 2025). I-10 is shown in red, US-90 in orange, and CSX tracks in gray. To the west of the map is Slidell, Louisiana, and to the east is Mobile, Alabama.

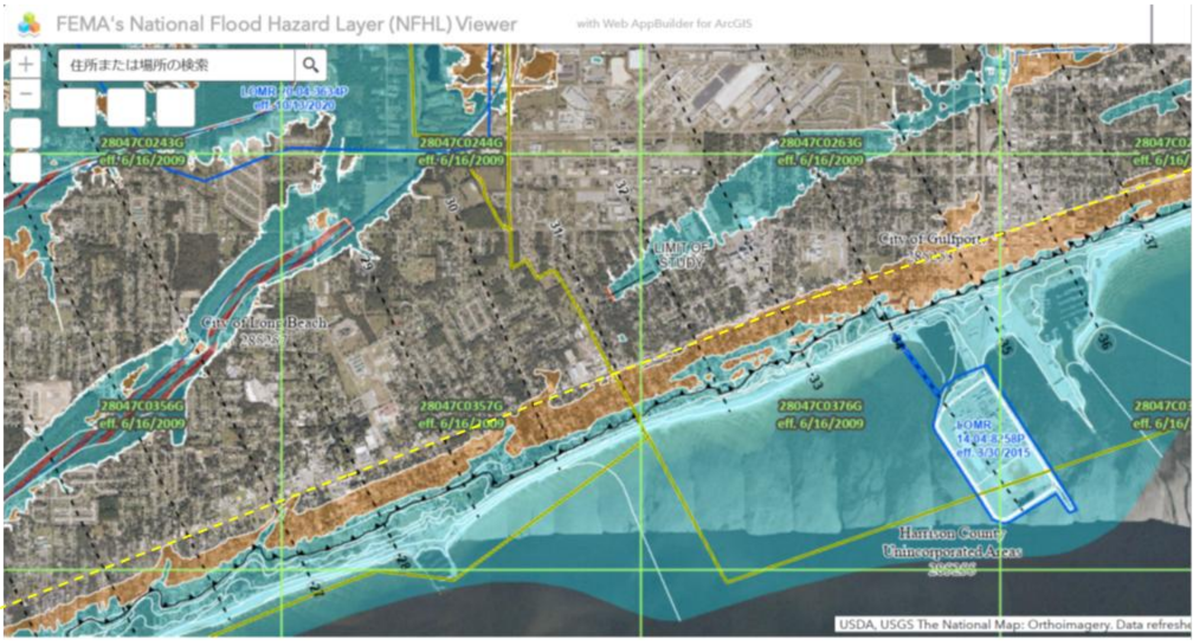


Figure 2. FEMA FIRM viewer image of Long Beach, Mississippi and Gulfport, Mississippi (FEMA, 2025). Blue shading indicates the 1% annual chance inundation zone, and orange shading indicates the 0.2% annual chance inundation zone. The black line indicates the shoreward extent of the V (velocity hazard) zone. The dashed yellow line indicates the location of the railroad. The US-90 highway runs directly adjacent to the shoreline.

Figure 3. Port Bienville, Mississippi. Left (Oct 2005): CSX railroad, with ballast scoured seaward. Right (May 2006): CSX railroad, repaired.

Figure 4. Waveland, Mississippi. Left (Oct 2005): Railroad berm scoured away by the surge. Right (May 2006): Railroad berm repaired and freight trains back in service.

Figure 5. Waveland, Mississippi. Left (Oct 2005): Railroad berm scoured seaward by the surge, and buoyant debris deposited on its seaward side. Right (May 2006): Railroad repaired, and large debris removed. Seaward is to the right.

Figure 6. Pass Christian, Mississippi. Left (Oct 2005): School bus straddling the railroad berm, after having been carried there by the surge. Right (May 2006): debris removed from the railroad berm.

Figure 7. Pass Christian, Mississippi. Left (Oct 2005): Wash-outs along the coastal road. Right (May 2006): Temporary repairs to the coastal road, with gravel.


Figure 8. Photo from MLITT (2025) showing the 2011 tsunami primarily confined seaward of the Sendai Tobu road freeway embankment in Miyagi Prefecture.


Figure 9. Photo from MLITT (2025) showing the 2011 tsunami primarily confined seaward of the national road #6 Soma Bypass highway embankment in Fukushima Prefecture.

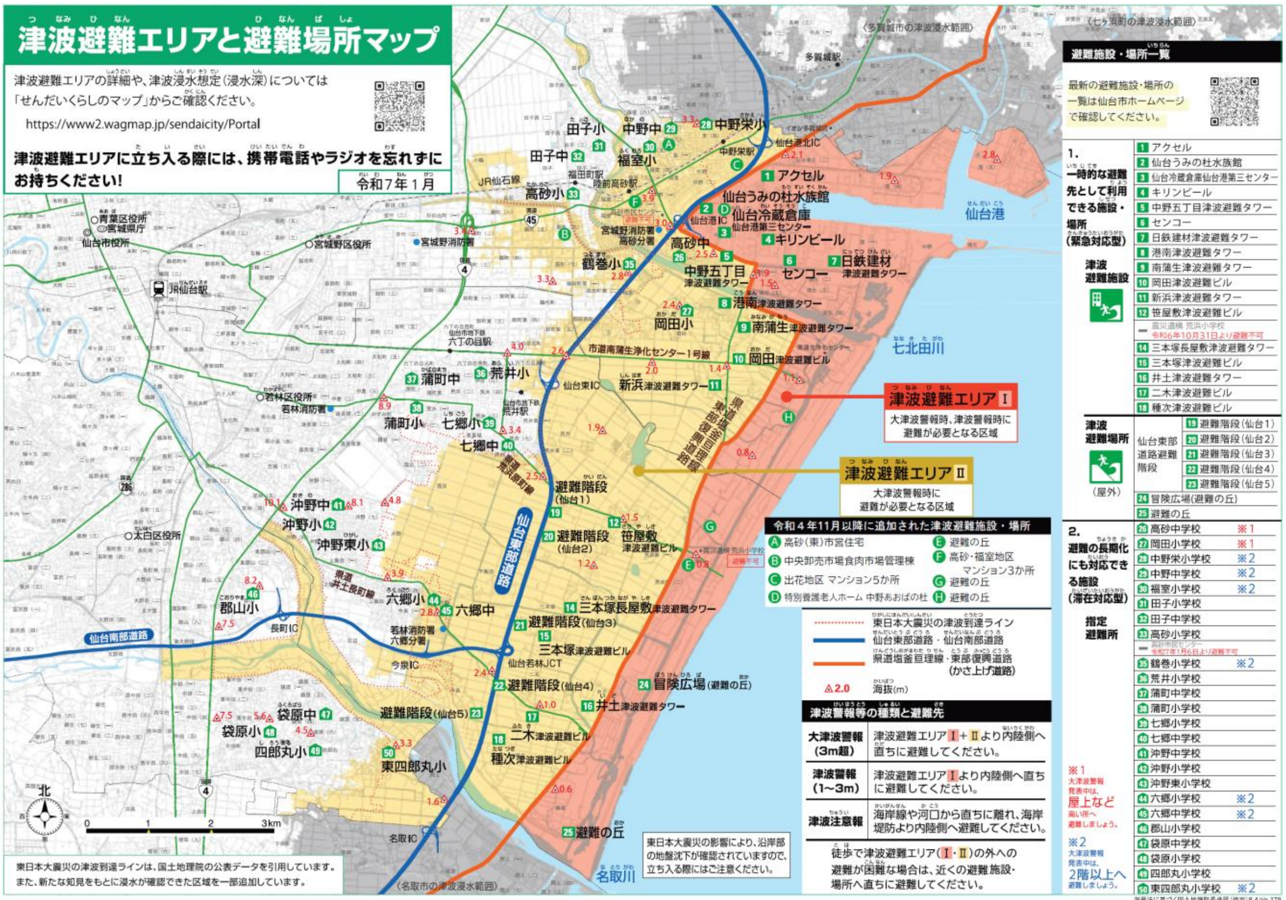


Figure 10. Tsunami evacuation map for Sendai, Japan (from Sendai City, 2025). Red shading indicates the Level 1 (approximately 100 year return period) tsunami evacuation area, and yellow shading indicates the Level 2 (approximately 1,000 year return period) tsunami evacuation area.

# 4 Discussion

The cases of road embankments mitigating inundation extent from the 2011 Tohoku tsunami serve as examples of how coastal or near-coast transport infrastructure can serve a secondary purpose as flood defenses. Even though tsunamis and storm surges are generated differently and have different hydraulic characteristics, they can be mitigated by similar structures (Bricker et al., 2016). Along the coastline of eastern Japan, which is exposed to both hazards, coastal embankment heights are determined by the greater of expected storm wave runup height and expected tsunami height, which itself is now determined for multiple return periods, or hazard levels (Suppasri et al., 2016). Storm surges are typically characterized by water levels that surge and then recede over the course of many hours, often accompanied by large, short-period wind waves. Near the Mississippi coast, the height of Hurricane Katrina’s storm surge was a maximum of 8 m, gradually running up and then receding over the course of about 12 hours, accompanied by wind waves of up to 17 m in height (Dietrich et al., 2010, 2011). Judging by the partial damage (not full damage) of the coastal highway in Figure 7, it can be inferred that these large wind waves broke offshore of the roadway, indicating the substantial protective effect of sandy foreshores (Lashley et al., 2022). Overland flow speed due to the storm surge itself can be estimated by assuming a trapezoidal prism of water advected onshore along a transect, from 8 m at the shoreline, to 1 m at the CSX tracks located 500 m inland, for a total of 2,250 $m^2$ of water. This corresponds to an onshore flow rate along the transect of of 0.1 $m^2/s$, thus a flow speed near the shoreline on the order of 10 cm/s. This is a significantly less energetic hazard than the 2011 Tohoku tsunami, under which Figure 8 illustrates much more rapid flow speed (based on the presence of whitewater and eddies) when impacting the Sendai Tobu road located 2 km inland from the shoreline. Drawing on the examples of the road embankments in Figs. 8 and 9 to illustrate how storm surge damage could have been reduced by such an embankment in Mississippi, is thus a conservative analysis.

Since the analysis of cost to elevate US-90 in Mississippi in the "Results" section is very coarse (state level), a slightly more focused cost comparison can be achieved by looking at county-level residential insurance claims from NFIP (2025) for Harrison County (on Figure 1, the western extent of Harrison County is Pass Christian on the east shore of St. Louis Bay, and the eastern extent is Biloxi, on the west shore of Biloxi Bay). Since US-90 runs along the shoreline of the entire county, it can be assumed that a raised US-90 would significantly protect most of Harrison County from inundation-related damage. NFIP (2025) indicates that a total of $1.2 billion in residential flood insurance claims were paid out in Harrison County. The length of US-90 within Harrison County is 42 km, or approximately 1/3 the total length of US-90 in the state. If this length of US-90 were to be elevated as outlined in the preceding paragraph, the corresponding construction cost would be $65 million. This construction cost is about 5% of the value of the insured residential damage that it could have helped prevent. This cost-benefit ratio contains both non-conservative assumptions and conservative assumptions. The non-conservative assumptions include the fact that residential damage also occurred in the backshore and back bay regions of Pass Christian (on St. Louis Bay) and Biloxi Bay. These backshore and back bay regions would not have been protected by an elevated US-90, because storm surge flooded into the mouths of these bays and inundated backshores and back bays from the bays themselves. Removing these regions from the cost-benefit ratio would make it less favorable. The conservative assumptions for the cost-benefit ratio includes the fact that the only benefits considered were direct damages to insured residential properties. Inclusion of commercial, industrial, and non-insured residential properties, in addition to infrastructure damages as well as indirect damages to commerce and livelihoods, would further reduce the cost-benefit ratio and lead to a more favorable argument. However, limitation in publicly available data do not allow a more detailed quantification of this.

Another assumption made in this analysis is that, unlike river levees designed to withhold floodwaters for many days or weeks, the coastal road/embankment here does not require seepage prevention measures such as sheet pile, a grout curtain, or a clay core/surface. This is because the duration of storm surge is on the order of hours, not days or weeks as river floods can be. In the case of Hurricane Katrina, the full timeline from beginning of surge runup to end of surge drawdown did not last longer than 12 hours (Dietrich et al., 2010, 2011). Nor is heavy concrete or stone armor cost included, as it is assumed that energetic waves are broken by the broad sandy beach (foreshore) in front of the road. This assumption is substantiated by Figure 7, in which the coastal road is seen with asphalt in place, with grass beside the road also present, whereas both of these would have been removed in the case of strong wave impact. The collapse of the side of the roadway shown appears to be due to scour caused by overland flow during storm surge drawdown. Another cost not included in the analysis is the property acquisition that would be required in the case where buildings exist in the footprint of the embankment's trapezoidal cross section, though such costs could be avoided if the Dutch concept of dijkhuizen (dike houses) were adopted (Chen et al., 2017).

In addition to the secondary benefit of coastal flood protection, elevation of major roads on fill could provide tertiary benefits as well, by requiring the placement of culverts that function as wildlife corridors in addition to drainage routes. Wildlife crossing structures such as culverts have been shown effective at connecting wildlife habitats across transport arteries (Smith & van der Ree, 2015) while also reducing road crashes due to interaction of drivers with wildlife. However, road elevation could also incur some adverse effects. One negative effect would be impoundment of floodwater that overtops the embankment, increasing the duration of flooding compared to what the inundation would be with only an at-grade road present. Another negative effect of an embankment could be exacerbated localized damage due to overtopping floodwaters raging down the landward slope of the embankment, potentially causing significant scour and incurring strong hydrodynamic forces on structures near the embankment (Seed et al., 2008).

Since the scope of the present study relies only on existing literature and historical data, an obvious question is how much protection a 10 ft high embankment relative to its 10 ft NAVD foundation elevation (USGS, 2025) would be able to provide. This number was chosen based on what could be socially acceptable without causing residents to feel like they are cut off from their beaches and the Gulf, along with the spatial average elevation of Hurricane Katrina's maximum surge along the Mississippi shoreline (20 ft NAVD). However, since the peak (in both space and time) maximum surge from Hurricane Katrina in Mississippi was approximately 26 ft NAVD (Dietrich et al., 2010), an embankment of 16 ft height (relative to its 10 ft NAVD foundation) would be needed to fully block this surge. Such a 16 ft height would be equivalent to that of the Galveston seawall, so is another number to consider. Using the same unit costs as above, raising the road by 16 ft across the entire state would incur a total cost roughly twice that of the 10 ft wall, about $411 million, which equals 2% of the total insured damage caused by Hurricane Katrina in Mississippi. This cost compares favorably to the expected annual damages of $1.1 billion statewide. If considering only Harrison County instead of the entire state, elevating the stretch of road by 16 ft in the county would cost $137 million, which is 11% of the insured residential damage it would help prevent in that county in the case of Hurricane Katrina.

# 5 Conclusion

Based on data from Hurricane Katrina in Mississippi and the 2011 Tohoku Tsunami in Japan, a case could be made that utilizing transport infrastructure for a secondary role as coastal flood defenses makes economic sense. Multifunctional flood defenses are common in the Netherlands (Anvarifar et al., 2017), where coastal dikes that serve a primary purpose of flood defenses are also utilized as transport arteries. In Japan, these roles are reversed, with transport the primary function, but coastal defense still rigorously planned into the design. In the US, the combination of coastal flood defense into transport infrastructure does not yet exist, but makes economic sense.

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# Author contributions (CRediT)

JDB: Conceptualization, Analysis, Writing.

# Data access statement

Not applicable.

# Declaration of interests

The author reports no conflict of interest.

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