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Urban Sinkholes in Coastal Cities of the Gulf of Mexico: The Interrelation of the Sedimentary Environment and the Urban Infrastructure in Coatzacoalcos, Veracruz, Mexico

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Abstract

Sinkholes in urban areas of coastal cities are a frequent phenomenon observed over the past few decades. The type of rock influences their development in the sedimentary environment and by anthropogenic works, such as urban drainage infrastructure and sewer systems. In this work, we conducted field visits to sites in the city of Coatzacoalcos, where we observed open sinkholes, fracturing, and subsidence of the concrete. To determine the relationship between sinkholes and the site's geology. We used data from sand sediment samples collected during a previous work at various locations of Coatzacoalcos city to measure grain size. The granulometric study found that most of the sediment volume in the urban area of Coatzacoalcos consists of coarse, medium, and fine sand, with grain sizes ranging from 0.40 to 0.15 mm. Another factor was the deterioration of concrete drainage and sewer pipes over the years of service, leading to cracks and fractures that eventually collapsed, creating openings and allowing sand to enter the pipes. This gradual development leads to a cavern that eventually collapses, forming a sinkhole.

Keywords

Sinkhole Development, Sinkholes in Sand Sediments, Coastal Sedimentology, Geological Risks, Urban Problems, Gulf of Mexico, Urban Infrastructure

1. Introduction

1.1. Background

A sinkhole is a depression in the ground that has no natural surface drainage. When it rains, the water stays inside the sinkhole and drains into the subsurface. Sinkholes are common in karst terrain, but they are not a mandatory factor; many sinkholes occur in other sedimentary environments. Sinkholes are dramatic because the land usually remains intact for a time until the underground spaces become too large. When support for the land above the spaces is insufficient, a sudden collapse of the land surface can occur [1] [2].

In this work, we investigated the dominant factors that cause sinkholes due to urban cover collapse in sandy soils, including pipe failures in the drainage and sewage systems and sediment grain size.

Given the importance of studying and monitoring sinkholes in urban areas, many studies have examined the economic losses they cause and the risks they pose to citizens.

There are many works on the detection of caverns in karst environments that have not yet collapsed but will collapse in the future, forming sinkholes. Some studies used geophysical methods such as gravimetry, ground-penetrating radar (GPR), electrical resistivity tomography (ERT), or a combination of these [3]-[7].

Some studies evaluated soil susceptibility to sinkhole development in specific areas under different geological environments and developed risk maps [8]-[15]. Other studies used simulation models to predict sinkhole formation driven by various natural and anthropogenic factors [16]-[21].

Likewise, others used morphological and morphometric parameters, existing databases, information from Google Earth, Geographic Information Systems (GIS), aerial photographs, and drones to collect images for their analyses [22] [23].

On the other hand, [24] conducted paleoenvironmental interpretation of karst environments along the Florida coast of the Gulf of Mexico in relation to terrestrial climate change. [25] correlated the spatial and temporal distribution of sinkholes with the existing fracture and folding system, to correlate these geological events with the occurrence and development of sinkholes.

[26] evaluated the causes and consequences of large-scale sinkholes, considering the implications of economic damage and the risk that these sinkholes may represent. [27] investigated the dominant factors that cause sinkholes due to urban cover collapse in sandy soils to propose more effective mitigation measures and thus decrease the frequency of sinkhole development and occurrence. [28] made a description of a large sinkhole associated with landslides in gypsum scarps and gypsum karsts.

1.2. Sinkholes in Urban Areas of Coastal Cities

Sinkholes in urban areas of coastal cities, such as Coatzacoalcos, have been a frequent phenomenon observed over the past few decades. The type of rock influences their development in the subsoil, namely the coastal sedimentary environment, which is mainly composed of sand deposited by ocean currents and wind, as well as by anthropogenic works such as urban drainage infrastructure and sewer systems.

In Coatzacoalcos, this phenomenon has been observed continuously for the past 20 years. However, despite this frequency, a systematic record of sinkhole collapses and appearances in the city has not been kept. Sinkhole appearances have resulted in economic losses for municipal authorities due to the cost of repairing concrete streets. Furthermore, there is a risk that vehicles will fall into these sinkholes.

The first published reports on sinkholes in Coatzacoalcos appeared in 2015 [29]. Before this date, there were no records of sinkhole formation. However, some citizens reported observing sinkholes forming approximately 10 years before 2015. Between 2018 and 2020, more reports were published [30]-[32], and from 2023, the number of published reports has increased considerably.

The city and port of Coatzacoalcos is the second most populous coastal city in the state of Veracruz, Mexico (310698 inhabitants), after the city and port of Veracruz (607209 inhabitants) [33] [34]. Economically, Coatzacoalcos is the second most important city on the Veracruz coast, after Veracruz [33] [34].

These two factors (population and economy) make the city of Coatzacoalcos highly relevant as a commercial, industrial, and economic hub, not only in the state of Veracruz, but also along the entire Mexican Gulf Coast. Furthermore, with the development of the Interoceanic Corridor, which will commercially link the Gulf of Mexico (Coatzacoalcos, Veracruz) with the Pacific Ocean (Salina Cruz, Oaxaca), the city of Coatzacoalcos will continue to grow in the coming years [35].

2. Location of the Study Area

Figure 1. Location of the city and port of Coatzacoalcos on the southern Gulf of Mexico. The city is north of the Isthmus of Tehuantepec. The Isthmus of Tehuantepec is the narrowest part of Mexico between the Gulf of Mexico and the Pacific Ocean (Topographic-map.com, https://es-mx.topographic-map.com/).

The port of Coatzacoalcos is on the southern coast of the Gulf of Mexico, in the southern part of the state of Veracruz, Mexico (**Figure 1**). The boundaries of the municipality of Coatzacoalcos are to the north, the Gulf of Mexico coastline; to the east, the municipality of Agua Dulce; to the south, the municipalities of Moloacán, Ixhuatlán del Sureste, Nanchital, and Cosoleacaque; and to the west, the municipality of Pajapan. The municipality of Coatzacoalcos has a land area of 309.2 km^2 [36].

The urban area of the city of Coatzacoalcos is in zone 15Q between UTM coordinates 334769 mE to 353627 mE and 2009282 mN to 2002209 mN (**Figure 2**) (Google Earth).

70.4% (32.6 km^2) of the urban area is on coastal dunes (highlands), and 29.6% (13.7 km^2) is on alluvial sediments (lowlands). The total area of the urban zone is 46.3 km^2. Only a small proportion of the study area lies outside the urban area of Coatzacoalcos; this is on marshland filled with sediment (lowlands) (Google Earth Pro, 2026).

Figure 2. Urban area of the city of Coatzacoalcos, which is located in zone 15Q between the UTM coordinates of 334769 mE to 353627 mE and from 2009282 mN to 2002209 mN. (Google Earth Pro, 2026 Image).

3. Geology of the Study Area

According to [37], the urban area of the city of Coatzacoalcos presents the following geology:

In the northern part of the Coatzacoalcos urban area, there are deposits of unconsolidated sediments formed from Quaternary aeolian sand of Holocene age (10,000 - 8000 years). These sediments are distributed along the Veracruz coastline in the Gulf of Mexico, forming coastal dunes (higher areas of the city).

In the central part of the urban area, unconsolidated alluvial sediments composed of fine gravel, sand, and silt from the Holocene (Quaternary) period (4000 - 3000 years) are present. These sediments are distributed along the Veracruz coastline in the Gulf of Mexico, forming coastal dunes (higher areas of the city). These alluvial sediments form the city's low-lying areas.

Towards the south and west-central parts of the urban area, there are deposits of unconsolidated marsh sediments composed of sand, silt, and clay from the Quaternary, of Holocene age (10 - 8 thousand years), which contain abundant organic matter (in the lower areas of the city).

Figure 3 shows the distribution of Quaternary deposits, and Table 1 presents the locations of the sinkholes inspected in the urban area of the city of Coatzacoalcos.

Figure 3. Distribution of Quaternary sediments in the urban area of the city of Coatzacoalcos. Aeolian sediments forming coastal dunes (sand) are in the north. Alluvial sediments (fine gravel, sand, and silt) are in the central part. Palustrine sediments with organic matter are in the south and west. The locations of the sinkholes (SH 1 - 12) inspected during the field surveys are also shown (Google Earth Pro, 2026 Image).

4. Methodology

We compiled information from previous studies on sinkholes and their implications for urban areas in various cities. Subsequently, we obtained information about the geology of the urban area of Coatzacoalcos, as well as a recent study by [38] in the Coatzacoalcos Paleolagoon area.

Field trips were conducted to sinkhole locations to gather information on sinkhole locations, sediment types, and their relationship to the city's urban infrastructure. Additionally, we identified locations and made notes during the visits where sinkholes had previously existed.

We visually identified new concrete on the sites of old sinkholes repaired by the municipal administration, which differs in color from the old concrete on the streets.

We used granulometry data for unconsolidated sediments distributed across the urban area of the city of Coatzacoalcos from [38] to analyze the relationship between sinkhole location, geology, and urban infrastructure.

5. Work Development

We conducted field visits to sites in the city of Coatzacoalcos where open sinkholes were observed, as well as to sites where fracturing and subsidence of the concrete in the streets were already visible. A record was kept for each site visited, including each sinkhole, its location, photographs, verification of the sediment type, and identification of the existing infrastructure. We also recorded notes on possible causes of their development and progression.

Based on the work developed by [38], we took information from the granulometric analysis of sand samples obtained in the study area to correlate the connection between geology (granulometry of sand sediments) of the urban area, the development of the sinkholes, and the existing municipal infrastructure (drainage and sewage system). **Figure 4** shows the locations of the sediment sample sites.

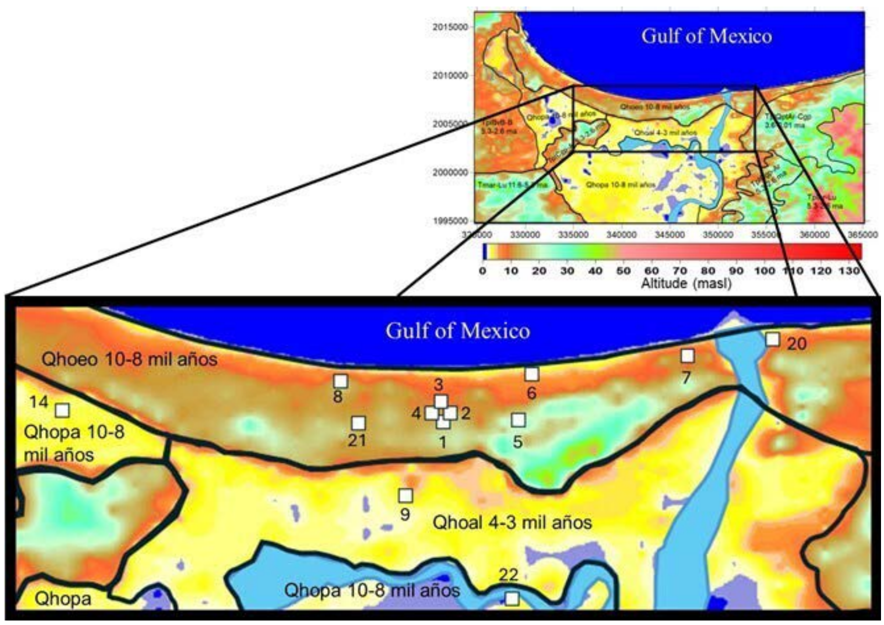

Figure 4. Location of sediment sampling sites for granulometric analysis. The white squares represent the location of the samples collected in the study area (modified from [32]).

We recorded the locations of each sinkhole visible at the time the fieldwork was carried out (**Figure 5**) and visually identified the city's drainage and sewer system ducts at sites where they were observable, along with their condition of deterioration. In sinkholes SH 1 and 2, we observed by direct inspection that the drainage pipe had collapsed, and a few days later, the municipality excavated to replace the damaged pipe. In sinkholes SH 3, 7, 9, 10, 11, 12, the municipality carried out excavations to replace damaged drainage pipes and repair sewers. At SH 4, the concrete slab shows sinking and fractures, and in the sinkholes at SH 5 and 6, we inferred damaged pipes because they were not visible.

It is worth noting that no specific criteria were used to select the sinkhole locations. We conducted surveys in the city's high-traffic, densely populated areas, where we observed sinkholes in the higher part of the city, which contains sandy sediments of eolian origin (old dunes).

Figure 5. Location of open sinkholes (red circles SH) in the urban area of the city of Coatzacoalcos (Google Earth Pro Image).

The following are photographs of some of the sinkholes studied in the urban area of Coatzacoalcos, Veracruz (Figure 6), along with their coordinates (Table 1).

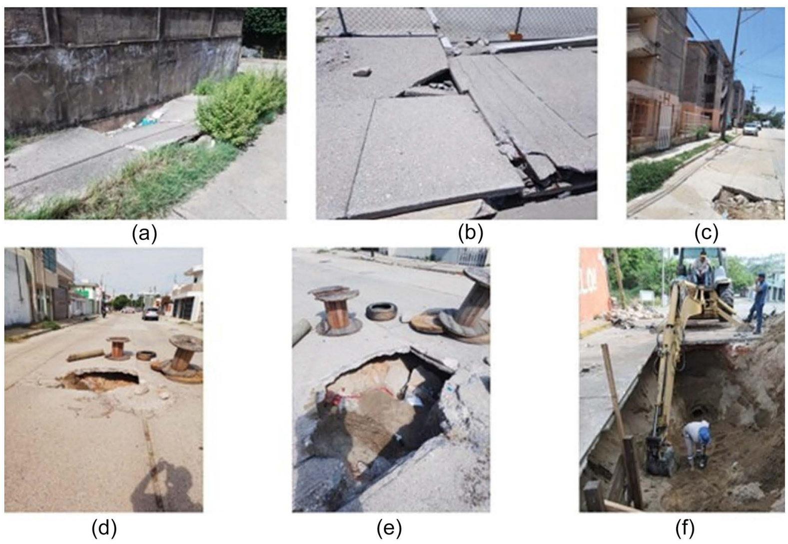

Figure 6. Open sinkholes in the urban area of Coatzacoalcos. (a) Sinkhole SH-2, (b) Sinkhole SH-5, (c) Sinkhole SH-6, (d, e) Sinkhole SH-8, (f) Sinkhole SH-9.

6. Results

Open sinkholes were identified, with surface-collapse diameters ranging from 1.5 m to 4 - 5 m and depths of 1 - 4 m. The streets of Coatzacoalcos are concrete slabs. These labs cause the sinkhole to initially develop beneath the concrete slab, remaining invisible to the citizen.

Table 1. UTM coordinates of the sinkholes inspected during the field tours.

SINCKHOLE	East Coordinates (m)	North Coordinates (m)
SH-1	345012.00	2006191.00
SH-2	344820.00	2006195.00
SH-3	344807.00	2006202.00
SH-4	344209.00	2006800.00
SH-5	344613.00	2007379.00
SH-6	345149.00	2007045.00
SH-7	345272.00	2006201.00
SH-8	345997.00	2006675.00
SH-9	346472.00	2005528.00
SH-10	349337.00	2007232.00
SH-11	349407.00	2006782.00
SH-12	348944.00	2006619.00

When the cavern becomes large enough, the concrete slab begins to fracture, and subsidence begins. Sometimes, subsidence is slow, as is the fracturing of the concrete slab; in other cases, a sudden collapse occurs due to an abrupt increase in the slab's weight. The weight on the concrete slab causes fractures, which subsequently lead to the slab's collapse and the formation of the sinkhole.

Although sinkholes in the city have been a recurring phenomenon over the past 20 years, during that time, authorities in each municipal administration carried out repair work, resulting in considerable economic losses and posing a risk to drivers who fell into them.

There is very little official or unofficial information on the economic costs of repairing concrete slabs and drainage pipes, because access to the municipal administration's financial reports is unavailable. Another source [29] reports that the municipality of Coatzacoalcos spends between 5 and 6 million Mexican pesos annually (approximately US$280,000 to US$335,000).

To determine the relationship between the occurrence of sinkholes and the site's geology, we took data from a previous work [38] where sand sediment samples were collected from different locations to measure grain size (**Figure 4**) and the amount of sediment retained by each sieve, recording the percentage retained for each grain size (**Table 2**).

The open sinkholes in the urban area of Coatzacoalcos are in sand sediments that constitute the ancient dunes along the coastline (**Figure 5**).

We also calculated the volume of sediment passing (%) through each sieve to determine the size of the grains that make up the largest volume of sediment (sand) in the urban area of Coatzacoalcos (**Table 3**).

Table 2. Sediment grain size and percentage retained in samples taken in the urban area of Coatzacoalcos. The largest volume retained (bold font) is between 0.40 and 0.15 mm [38].

Particle	Retained volume (%)												
Size (mm)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S14	S20	S21	S22
2.0000	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	6.90	0.88	0.17	0.00	0.68
0.8500	0.64	0.78	0.07	0.08	0.55	0.39	0.02	0.02	7.35	7.69	0.44	1.41	9.15
0.3550	**10.18**	**3.69**	**8.24**	**8.64**	**8.78**	**9.60**	**0.32**	**22.03**	**22.88**	**22.45**	**22.50**	**16.27**	**23.32**
0.2500	**49.28**	**45.15**	**42.85**	**36.02**	**33.35**	**29.15**	**33.08**	**47.00**	**27.99**	**28.03**	**54.92**	**47.89**	**26.86**
0.1800	**23.56**	**35.00**	**39.03**	**42.15**	**44.06**	**44.04**	**50.28**	**22.57**	**24.23**	**27.83**	**17.02**	**20.45**	**22.86**
0.1500	**5.90**	**6.13**	**4.74**	**6.07**	**8.08**	**10.00**	**10.25**	**4.86**	**5.34**	**5.38**	**3.34**	**4.86**	**5.37**
0.1250	4.03	4.14	2.65	3.95	3.44	3.72	3.76	2.24	2.89	3.23	1.09	3.34	4.21
0.090	2.21	2.56	1.30	1.90	1.51	1.67	1.91	0.96	1.26	2.60	0.50	1.92	3.84
0.075	1.23	0.97	0.35	0.45	0.16	0.48	0.24	0.15	0.68	0.54	0.01	2.02	2.14
Les than	2.98	1.57	0.76	0.75	0.07	0.62	0.13	0.16	0.48	1.37	0.00	1.83	1.57

Table 3. Volume of grains passing through each sieve in the samples from the urban area of Coatzacoalcos. The large volume passing through (bold font) ranges from 0.40 to 0.15 mm.

Particle	Retained volume (%)												
Size (mm)	S1	S2	S3	S4	S5	S6	S7	S8	S9	S14	S20	S21	S22
2.0000	100.0	100.0	100.0	100.0	100.0	99.68	100.0	100.0	93.10	99.12	99.83	100.00	99.32
0.8500	99.36	99.22	99.93	99.92	99.45	99.29	99.98	99.98	85.75	91.43	99.39	98.59	90.17
0.3550	**89.18**	**95.53**	**91.69**	**91.28**	**90.67**	**89.69**	**99.66**	**77.95**	**62.87**	**68.98**	**76.89**	**82.32**	**66.85**
0.2500	**39.90**	**50.38**	**48.83**	**55.26**	**57.32**	**60.54**	**66.58**	**30.95**	**34.88**	**40.95**	**21.97**	**34.43**	**39.99**
0.1800	**16.34**	**15.38**	**9.80**	**13.11**	**13.27**	**16.50**	**16.30**	**8.38**	**10.65**	**13.12**	**4.95**	**13.98**	**17.13**
0.1500	**10.45**	**9.24**	**5.07**	**7.04**	**5.18**	**6.50**	**6.05**	**3.52**	**5.30**	**7.74**	**1.61**	**9.12**	**11.76**
0.1250	6.42	5.11	2.42	3.09	1.74	2.77	2.29	1.27	2.42	4.52	0.51	5.78	7.55
0.090	4.20	2.55	1.11	1.19	0.23	1.10	0.38	0.31	1.15	1.91	0.01	3.85	3.71
0.075	2.98	1.57	0.76	0.75	0.07	0.62	0.13	0.16	0.48	1.37	0.00	1.83	1.57
Les than	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Using the values from **Table 3**, we plotted a graph of sediment volume (%) passing through the sieve versus particle size (mm) (**Figure 7**).

We found that most of the sediment volume in the urban area of Coatzacoalcos consists of coarse, medium, and fine sand with grain sizes ranging from 0.40 to 0.15 mm (**Figure 7**). This range of grain sizes explains the ease of grain movement when saturated with water and when water flow is present. Therefore, we observed a relationship between sediment characteristics and sinkhole development.

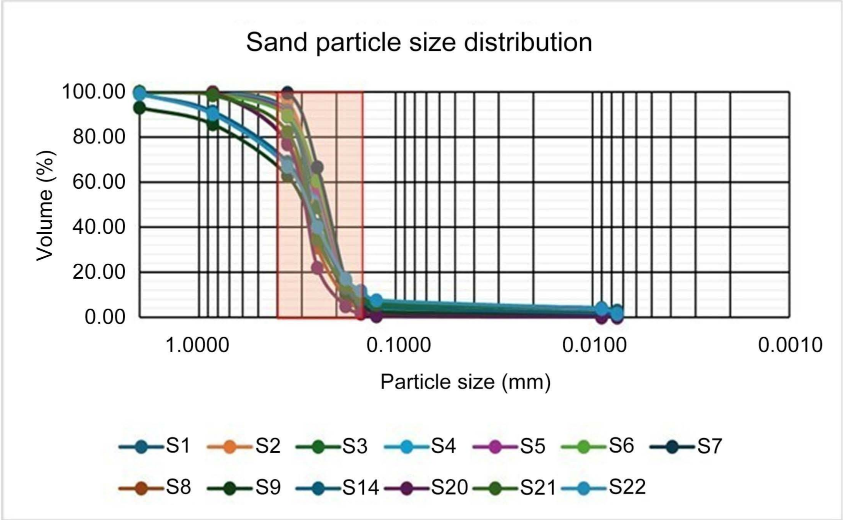

Figure 7. Particle size distribution of the sediment (sand) in the urban area of Coatzacoalcos. The largest volume of sediments corresponds to coarse to fine sands, with a grain size between 0.40 and 0.15 mm.

Samples S1 - S8 and S20 - S21 are in the area where a considerable number of sinkholes have developed. Samples S1 - S7 have a total grain size distribution (0.40 - 0.15 mm) ranging from 97.37% to 82.76%, consisting of coarse to fine sand of aeolian origin.

Samples S 8, S 20, and S 21 have a volume between 76.68% - 76.46% with a grain size of 0.40 - 0.15 mm. These sand sediments are associated with ancient channels of the Coatzacoalcos Paleolagoon, through which freshwater flowed and emptied into the sea.

Sample S9 is to the south, outside the area where the sinkholes have developed. This sample has a volume of 60.45% with a grain size of 0.40 - 0.15 mm. These sediments are of alluvial origin.

Samples of marsh sand S 14 and S 22 are outside the area of sinkhole development. Their total grain-size volume (0.40 - 0.15 mm) is 64.46% and 59.30%, respectively.

The composition of sand sediments in the urban area of Coatzacoalcos is very similar in both the area with and without sinkholes. However, analysis of samples from the sinkhole area showed a higher percentage of grain sizes between 0.40 and 0.15 mm (97.37% and 76.46%), whereas in the sinkhole-free area, the percentages were lower (64.46% and 59.30%).

Therefore, we observed that grain size influences the movement of water-saturated sands. However, this is only one of the factors that promote sinkhole development in the urban area of Coatzacoalcos. It should be noted that the area with sinkholes is the most populated and has the most extensive hydraulic infrastructure. In contrast, the area without sinkholes is lowland, with a water table at a few centimeters underground, with a small population and limited hydraulic infrastructure.

Another element related to both factors (sinkhole development – sediment grain size) is the infrastructure of the sewer and drainage system. Most of the sinkholes presented collapsed pipes.

Table 4 shows the volume percentages for grain size 0.40 - 0.15 mm.

Table 4. Total volume of grain size (0.40 - 0.15 mm) of each sample of sand sediments obtained inside and outside the area where sinkholes have developed in the city of Coatzacoalcos, Ver.

Volume of grain size between 0.40 - 0.15 mm of each sample (%)												
S1	S2	S3	S4	S5	S6	S7	S8	S9	S14	S20	S21	S22
82.7	90.4	89.2	88.1	88.9	86.9	97.3	76.6	60.4	64.4	76.3	76.5	59.3

7. Causes

The combination of sedimentary characteristics (sand) and the age of the sewer and drainage system's construction materials favors the development of sinkholes in the city of Coatzacoalcos.

The pipes are concrete, and according to [39], concrete pipes have a lifespan of 50 - 60 years under optimal conditions. Over time, the pipes crack and eventually collapse. The collapse allows sediment and sand to enter the drainage and sewer system.

Water from the drainage system seeps into the subsoil due to fractures in the pipes. When pipes collapse, the water causes the sand surrounding the collapse to shift toward the pipe, entering the drainage pipes and creating a void or cavern. Over time, the cavern expands until it collapses the concrete slabs that form the street pavement, resulting in sinkholes (Figure 8).

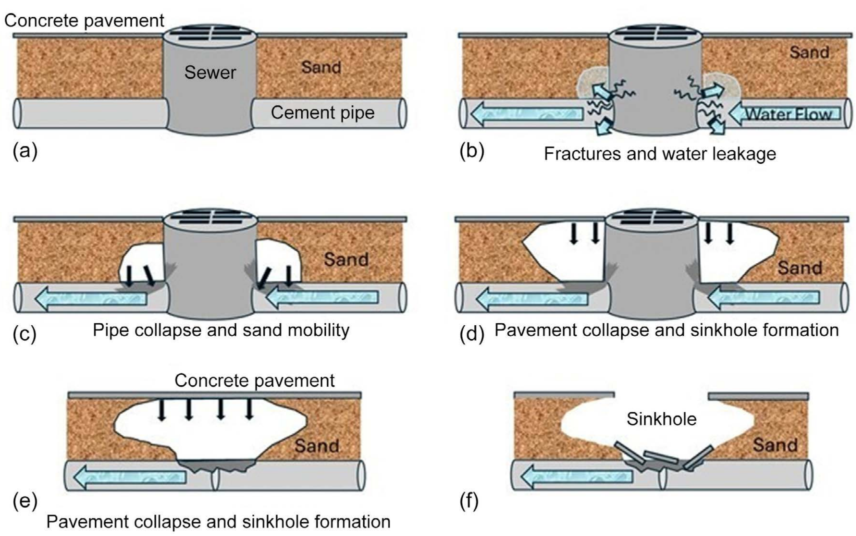

Figure 8. Model of the sinkhole development sequence in the city of Coatzacoalcos. (a) Optimal conditions of the drainage and sewer system. (b) Over the years, fractures appear in the pipes, and water infiltrates the subsoil. (c) The fractured areas collapse, and the water-saturated sand moves inside the pipe, initiating the formation of a small cavern. (d) The cavern grows until the roof, formed by the street's concrete slab, collapses, creating a sinkhole. (e and f) The collapse of the concrete slab and the formation of a sinkhole occur when two pipes of the drainage and sewer system meet.

As can be observed, the conditions of the drainage and sewer system pipes, due to the useful life of the construction material and the characteristics of the urban area's sediments, are factors that determine the development of sinkholes in the urban area of Coatzacoalcos.

8. Implications

In this case, there are two important implications: the economic impact and the risk to citizens.

Economically, the continuous appearance of sinkholes across the city forces municipal authorities to carry out repair and rehabilitation work in affected areas, which has represented a high and ongoing cost [29]; in its place, the municipal authorities could allocate these funds to other infrastructure projects in the city.

Citizens face a high risk because repairs and rehabilitation of the affected areas cannot be carried out as quickly as desired. Especially at night when drivers are at constant risk of falling into them.

9. Conclusions

The characteristics of the sediments that form the subsoil of the urban area of Coatzacoalcos, and the materials used in the drainage and sewer system pipes, are factors that favor the development of sinkholes in the city.

The granulometric study of sediment grains revealed that in the urban area of Coatzacoalcos, where sinkholes occur, the subsoil sediments consist of coarse, medium, and fine sand, with 97.37% - 76.46% of the sediment volume falling within the 0.40 - 0.15 mm grain-size range. Sand that is 100% saturated with water facilitates its flow or movement from one place to another.

The deterioration of concrete drainage and sewer pipes over the years of service causes cracks and fractures that eventually collapse, creating openings and allowing sand to enter the pipes. This gradual development leads to a cavern that eventually collapses, forming a sinkhole.

Therefore, we observe that there is a relationship among the characteristics of the subsurface sediments, the type of pipe material, and the development of sinkholes.

It is important to note that this work did not evaluate other factors that may contribute to sinkhole development, such as rainfall during storm seasons and vehicular traffic loads on concrete street slabs.

Furthermore, constant monitoring of the drainage and sewer systems, along with the gradual, scheduled replacement of old pipes with more resistant, durable materials, may be the best option for reducing the frequency of sinkholes. These actions can also significantly reduce the risk to citizens and generate substantial savings for the municipal administration.

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Conflicts of Interest

The authors declare no conflicts of interest.

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