# THE GREAT CHICAGO FLOOD

## Analysis of Chicago's 2nd Great Disaster

*By Jon Wren, Ph.D., P.E*

*In the early morning of April 13, 1992, dozens of downtown Chicago buildings started to mysteriously flood. Soon flooding knocked out utility services to more than 100 buildings. And the worst was yet to come. Flood water seeped into subway tunnels, shutting down the entire subway system. A major expressway inexplicably flooded, causing shutdown of several lanes of traffic. Hundreds of thousands of workers were sent home. Paralysis quickly gripped one of the nation's major economic centers. It took six days to plug the source of floodwater, and over a month and $5 million to dewater building basements. The cost of the flood would ultimately total approximately $1 billion.*


*Figure 1: Chicago freight tunnel network and location of tunnel breach beneath the North Branch of the Chicago River at the Kinzie Street crossing. (Source: What the Freight Tunnels Mean to Chicago, Chicago Freight Tunnel System, Chicago Tunnel Terminal Corporation, 1928.)*

The source of the underground flood was the North Branch of the Chicago River, pouring into a breeched section of an abandoned freight tunnel crossing beneath the river at Kinze Street. The tunnel was part of a 62 mile network of abandoned freight tunnels, originally built in the early 1900s (*Figure 1*), crisscrossing downtown Chicago and connecting to building basements. Six months before the flood, two dolphin pile clusters protecting the southeast abutment of the Kinzie Street Bridge were removed; the clusters were relocated approximately three feet to the south (unwittingly closer to the tunnel), and new piles were driven (*Figure 2* and *Figure 3, page 36*). The tunnel breach was recognized prior to the flood and contracts were already in progress to repair the tunnel.

On this 15th anniversary of the Chicago's second great disaster, the causes of the flood are revisited. At the time of the Great Chicago Flood, the effects of pile driving on nearby buried structures had not been studied in detail in geotechnical literature. To understand the effect of the dolphin pile driving on the freight tunnel, a geotechnical model was developed to study the effects of single pile driving and multi-pile driving on tunnel loads (*Figure 4, page 36*). The model replicated the performance of the Kinzie Street bridge dolphin clusters. Namely, tunnel failure was predicted after driving these pile clusters closer to the tunnel face, as in 1991. The model also explained the following: the dramatic load increases on the freight tunnel as dolphin piles were driven closer and closer to the structure, the cause of the tunnel breach, and the inundation of the tunnel.

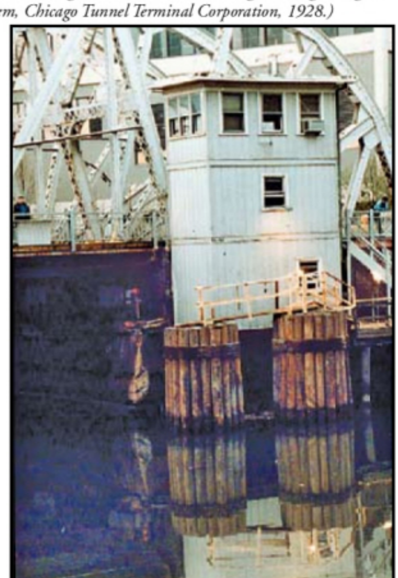

*Figure 2: Dolphin pile clusters at Kinzie Street Bridge.*

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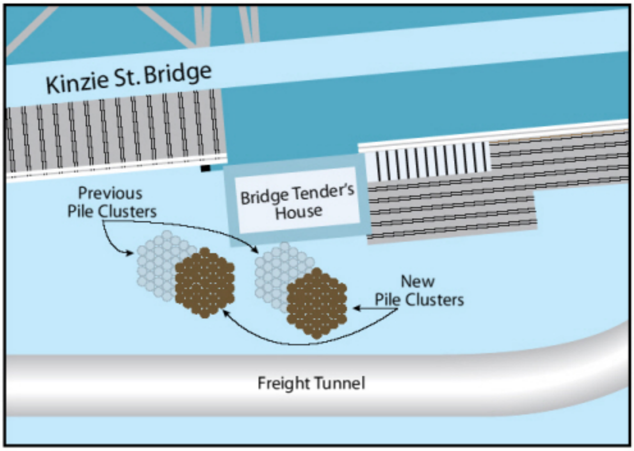


*Figure 3: Dolphin pile cluster locations: pre-1991 and as installed in 1991.*

## Tunnel Construction and Use

The Chicago freight tunnel system consists of 62 miles of hand constructed tunnels. Construction started in 1901 and was substantially complete by 1909. Night-shift workers hand excavated tunnel sections, followed by day-shift crews who com-pleted the section's liner. The liner consisted of unreinforced concrete, dry packed behind wooden forms (*Figure 5, page 37*). The tunnel invert varies between 20 and 50 feet below river levels.

The original intent of the tunnel system was to carry telephone and telegraph wires and cables. A 1903 ordinance allowed tunnel operators to officially transport merchandise such as coal, and remove solid waste from connections to the basements of over 80 buildings. The tunnel was equipped with a 24-inch gauge track and electric trolleys to convey merchandise. As a point of reference, at its zenith in 1928, the rail system employed 580 workers and had in excess of 3,300 rail cars to handle over 660 tons of goods annually. By 1959, a lack of demand and funds to repair equipment caused the freight system to be functionally abandoned. Currently, the tunnel system houses power and fiber-optic cables.

## Single Pile Behavior

Prior to the inundation of the freight tunnels, photographs of the tunnel breach showed recently driven dolphin piles close to, but not penetrating, the tunnel liner (*Figure 6* and *Figure 7*). Clearly, a relationship existed between the driving of the new piles and the tunnel breach. Geotechnical literature is replete with discussions of the effects of single pile insertion on the effective soil stress and pore water pressure. Because tunnel loading may be affected by these changes, an explanation of the tunnel breach begins with a review of the soil behavior from single pile insertion.

When a pile is driven into the ground, it must displace a volume of soil equal to the volume of the pile. For penetrations up to approximately 10 pile radii, the ground surface will generally heave similarly to the mounding that occurs around a finger inserted into a bowl of sugar. At deeper penetrations, studies have shown that the soil displacement patterns are midway between those associated with expansion of a spherical cavity and those associated with the expansion of a cylindrical cavity. In the region of an inserted pile tip, the soil is severely disturbed and remolded. Once the pile tip has passed a given depth, little further vertical movement of soil occurs at that depth.

The soil disturbance decreases with distance from a driven pile. Because the soil is severely disturbed and remolded near the pile, the area of these irreversible deformations is called the "plastic zone." The radius of the plastic zone depends upon the undrained shear strength of the soil, soil shear modulus, and pile size (*Figure 8, page 38*). Beyond the plastic zone, more or less reversible deformations occur, and therefore, this outer zone is referred to as the "elastic zone." If a buried structure is located within the plastic or elastic zones, the structure will experience additional loading from the excess pore water pressure generated by the pile insertion and associated soil disturbance.

As a driven pile passes a given depth, the soil in the plastic zone will fail; its structure/fabric will be destroyed. The excess pore water pressure generated from this process may be modeled as a maximum at the pile face and decreases with the natural logarithm of the distance from the pile within the plastic zone (*Figure 8, page 38*) [Randolph (1979)]. The excess pore water pressure variation within this zone may be expressed as a function of the initial soil stress state, geometrical conditions, and soil properties. Outside the plastic zone, the soil has not failed but has nonetheless experienced an increase in excess pore water pressure. The excess pore water pressure in the elastic zone may be modeled as decreasing inversely with the square of the distance from the plastic zone boundary [Randolph (1979)].

## Pile Cluster Behavior

By their very nature, dolphin piles are driven in close proximity to one another. The piles driven near the Kinzie Street bridge abutments are no exception, as seen in *Figure 2 (page 35)* and *Figure 7 (page 37)*. From a geotechnical perspective, driving a pile next to another pile, or a tunnel for that matter, represents a deceptively complex configuration. These buried objects represent obstructions to the movement or flow of soil during pile driving. For example, previously driven dolphin piles obstruct the flow of soil radially away from a driven pile and alter the distribution of excess pore water pressure described above.

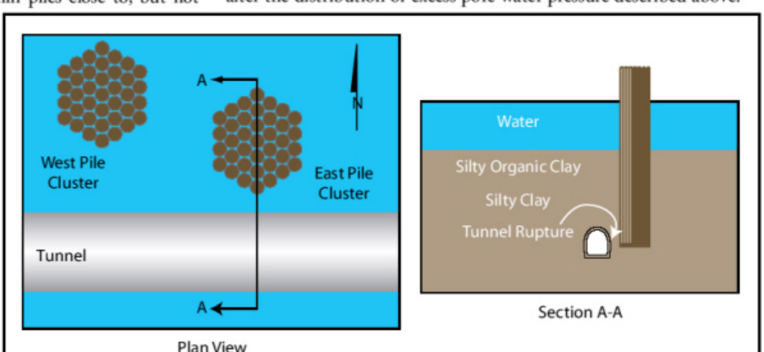


*Figure 4: Model of site conditions of the Kinzie Street pile clusters.*

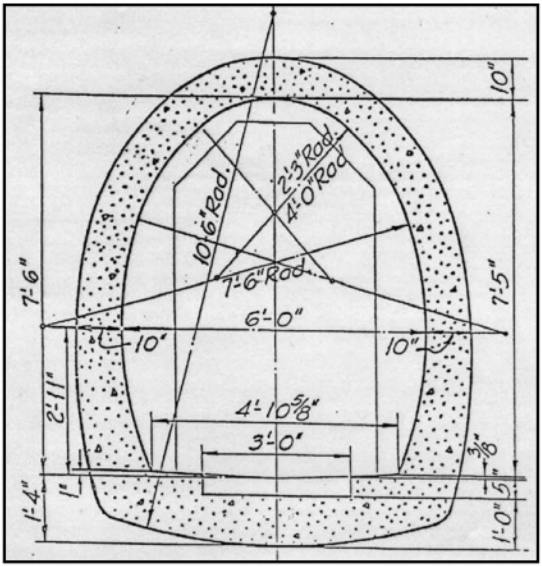


Figure 5: Section of the unreinforced concrete tunnel liner.

*Figure 6: Tunnel breach prior to inundation.*

*Figure 7: Piles visible through tunnel breach.*

To capture this phenomenon, the principle of superposition has been used, combined with excess pore water pressures from nearby piles [Cunze (1989)]. However, this superposition is restricted by soil mechanics. Excess pore pressure resulting from the superposition of two nearby piles may not exceed the maximum occurring at the pile face shown in *Figure 8 (page 38)*. In effect, insertion of two nearby piles may create a plastic zone greater than the simple union of their respective plastic zones, but may not exceed an excess pore pressure ceiling established at the pile face.

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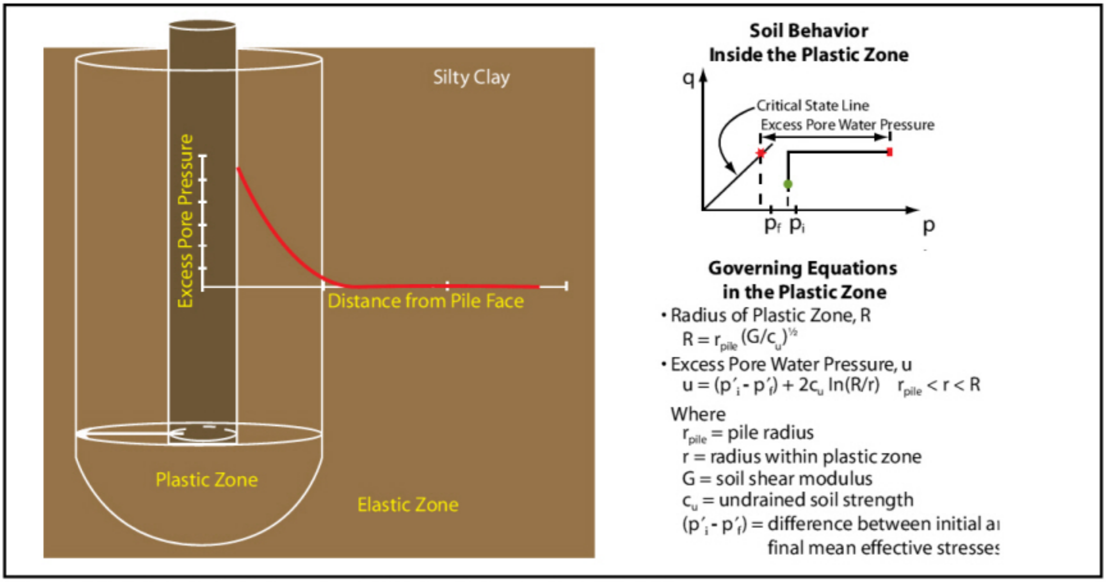


*Figure 8: Soil behavior inside the plastic zone for a single pile insertion (based on Randolph (1979)).*

When two piles are inserted next to each other, the in-place pile shadows an area into which no soil can flow when the second driven pile tip passes that depth. The volume of soil that would move into this shadowed region must be redistributed to the unshadowed region of the plastic zone. *Figure 9* demonstrates the conservation of this remolded volume for two piles driven next to each other. The figure schematically shows the plastic zone created around a driven pile (brown area around Pile #2) ignoring the presence of an adjacent pile and the redistributed plastic zone (green cross hatched area) considering the shadowing effect of the adjacent pile (Pile #1).

When an obstacle like a tunnel exists near driven piles, similar shadowing occurs. However, unlike the pile shadowing, which occurs entirely in the horizontal plane, tunnel shadowing occurs in the vertical plane. The soil tries to flow around the tunnel. For example, the top and bottom of the tunnel create minimal shadowing since the soil may easily flow over or below the tunnel. In contrast, the middle of the tunnel offers the maximum shadowing effect. Soil cannot easily flow around the middle of the tunnel. The volume of soil shadowed by the tunnel must be redistributed to the unshadowed plastic zone, i.e., the plastic radius would be larger. *Figure 10 (page 40)* demonstrates the conservation of this remolded volume for a pile driven near the tunnel.

## Tunnel Analysis

The effect of pile and tunnel shadowing underscores the importance of sequencing of dolphin pile installation. A sequence of pile insertion can be envisioned to minimize the shadowing effects, but would be impractical for installation of dolphin piles. A reasonable pile insertion sequence is therefore adopted to recognize pragmatic pile installation issues. The sequence is shown in *Figure 9*.

*Figure 11 (page 40)* shows tunnel loading resulting from pile driving at various distances from the tunnel face. The tunnel loading clearly increases with decreasing cluster offset distance. This result is a direct effect of plastic zones overlapping the tunnel at close distances. The irregular shape of the loading profile is a direct result of the pile and tunnel shadowing.

The tunnel loading shown in *Figure 11 (page 40)* explains a fundamental conundrum of the freight tunnel breach, namely,

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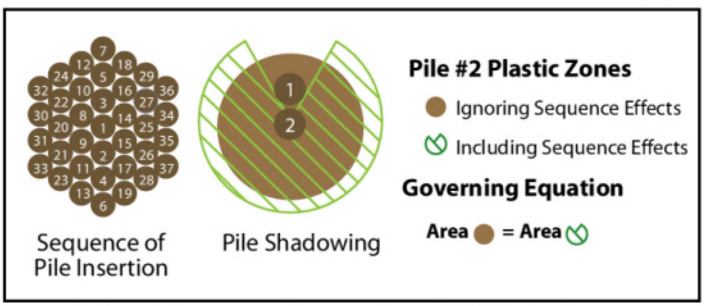


*Figure 9: Shadowing of plastic zone created by a previously inserted pile (Pile #1) and redistribution of the plastic zone around Pile #1.*

## References

M.F. Randolph, J.P. Carter, and C.P. Wroth, *Driven piles in clay – the effects of installation and subsequent consolidation*, Geotechnique 29 (1979) 361-393.

G. Cunze, A modified method for estimation of excess pore pressure generated by pile driving, in: Proceedings of the $12^{th}$ *International Conference on Soil Mechanics and Foundation Engineering* (1989) 1097-1100

why did the tunnel not breach during pre-1991 dolphin pile cluster driving? The solution is that the tunnel experienced dramatically higher loading from the close insertion of relocated dolphin piles. The unprecedented tunnel loads ultimately exceeded the capacity of the tunnel, causing the breach seen in *Figure 6* and *Figure 7 (page 37)*.

## Tunnel Flooding

Another puzzle posed by the tunnel breach was the delay of approximately six months between the breach and flood. The explanation for the delay lies in the seepage of river water through the soil outside the tunnel. This soil was relatively impermeable outside the tunnel, but was highly disturbed where the previous pile clusters had been extracted. The disturbance caused by the pile removal lowered the permeability of the affected region. The result was shortening the flow path and increasing the hydraulic gradient in the less disturbed soil outside the tunnel breach. Eventually, the seepage pressures and flow likely caused a failure of the soil mass outside the breach and resulted in a conduit forming between the river bottom and the tunnel. *Figure 12* shows river water flow through the disturbed soil created by the removal of the old dolphin cluster and into the tunnel breach.

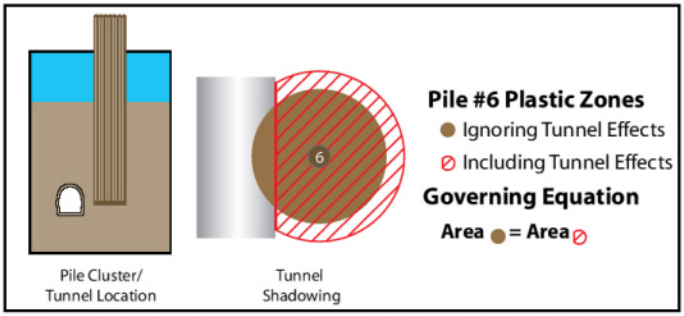


*Figure 10: Shadowing of plastic zone created by a tunnel and redistribution of the plastic zone around tunnel.*

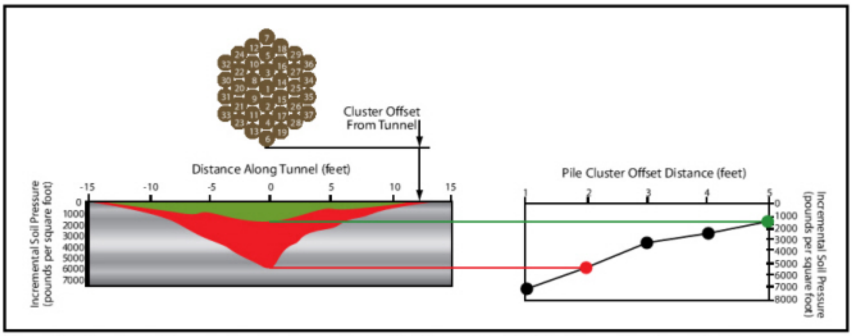


*Figure 11: Tunnel analysis results showing increased tunnel loading at tunnel mid-height resulting from pile cluster driving and the effect of cluster distance from the tunnel face.*

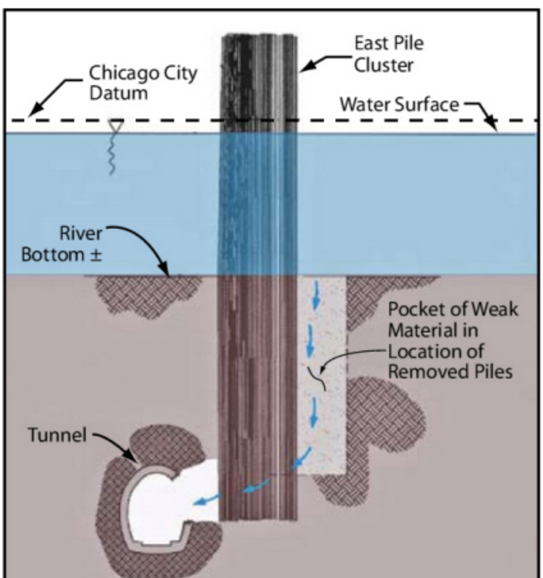


*Figure 12: Schematic of a likely fluid flow path into the tunnel through disturbed soil created by removal of the previous pile cluster.*

## Conclusion

Fifteen years ago, the Great Chicago Flood paralyzed one of the nation's major economic centers and resulted in damages estimated at $1 billion. The cause of the failure was a "perfect storm" of a little utilized network of freight tunnels connected to building basements throughout the city being breached beneath the North Branch of the Chicago River. The inundation of river water into the tunnel system functionally shut down Chicago and became a major economic disaster for the city, second only to Ms. O'Leary's bovine induced (as legend has it) conflagration in October 1871. The underground flood was caused by driving dolphin piles closer than planned to the freight tunnel resulting in a tunnel breach and eventual flooding of the tunnel system. The effects of the removal and driving of two dolphin pile clusters near the freight tunnel dramatically increased loading on the tunnel, and serve to explain the tunnel breach and subsequent flooding. Thus, Chicago's great underground flood provides many valuable lessons for engineers. For a recovered Chicago, the disaster is a distant memory and, as the old saying goes, "water under the bridge."▪

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