CHAPTER 7

Incorporating Natural Disasters into the Undergraduate Civil Engineering Curriculum: A Case Study of Hurricane Katrina and the Oso Landslide

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Introduction

In recent years, there has been an increased focus on the role of the engineering and scientific communities in providing the public with adequate protection against the effects of natural disasters. The ability of engineers and scientists to develop methods by which natural disasters can be better understood, more effectively predicted, and more accurately quantified has been subjected to increased scrutiny. A keen awareness of the role these professions play in defining the quality of life and the responsibility inherent to this role is crucial to their survival of the engineering and scientific professions. To that end, engineering education can be enhanced with the addition of learning objectives involving natural disasters and associated engineering failures. For undergraduate civil engineering students, these curricular bridges can serve as real-world examples of various engineering concepts, as well as the broader impacts of design errors, engineering judgment, and public policy. This paper will focus on curricular enhancements within a junior-level course in geotechnical engineering, a subdiscipline of civil engineering that focuses on earth materials and their interaction with the built environment. Most students enrolled in ABET-accredited civil engineering programs in the US are required to complete at least one course in geotechnical engineering at some point during their college career (typically in the junior year). As a case study, this paper will describe how natural disasters have been incorporated into the curriculum of *Civil Engineering 3020 – Geotechnical Engineering* at Merrimack College, a predominantly undergraduate, private institution in North Andover, MA in the US. These curricular enhancements could readily be adopted in other geotechnical engineering courses, as well as in courses on related topics. This paper will focus upon the levee failures during Hurricane Katrina and the extent to which this disaster exemplifies the curricular concepts of a typical undergraduate geotechnical engineering course. A discussion of the Oso, Washington, landslide of 2014 will also be presented.

Geotechnical Engineering Curricula

A typical undergraduate geotechnical engineering course introduces students to fundamental soil mechanics concepts such as soil composition and classification, compaction, groundwater flow, subsurface stress, settlement, and shear strength. Subsequent courses build upon these basic concepts to address topics in geotechnical design, such as slope stability analyses, the design of foundations and earth-retaining structures, and earthquake engineering.

At Merrimack College, the course outline of *Civil Engineering 3020 – Geotechnical Engineering* is presented as follows (the numbers in parentheses indicate the approximate number of 75-minute classes allotted to the topic):

1. Soil composition and classification (4)
2. Compaction (2)
3. Groundwater (3)
4. Stress (4)
5. Settlement (6)
6. Shear strength (5)
7. Applications of soil mechanics (3)

In this section of the paper, we provide a brief overview of each of these course topics, to guide the later discussion on Hurricane Katrina and the linkages between these course topics and the levee failures.

Soil Composition and Classification

The first topics typically covered in geotechnical engineering courses are the geologic origin of soils, physical properties for describing soils, and the soil classification systems used to determine the types of soil present at a site. In order of decreasing grain size, the four major soil types are gravels, sands, silts, and clays. Gravels and sands (coarse-grained soils) have larger grains than silts and clays (fine-grained soils). Gravels and sands derive much of their strength from the frictional forces that develop as the soil particles shear against one another when subjected to loading. In contrast, silts and clays derive much of their strength from cohesion, which can be caused by physical or chemical bonding. An additional fifth type of soil is organic soil. Organic soils contain a significant amount of organic material recently derived from decomposing plants or animals, are highly compressible, and are generally unsuitable for construction.[1]

Compaction

Compaction is the densification of soil via the removal of air voids, and can be performed in the field using a variety of techniques and equipment. Most construction projects require some sort of earthwork, and the compaction of placed fill must meet specifications to ensure that the soil will have adequate stiffness and shear strength. The compaction specifications for earth dams and levees are among the most stringent of any type of earthwork, due to the potentially catastrophic consequences of failure.[2]

Groundwater

Groundwater is the term commonly used to describe all subsurface water within the ground, which is located within soil voids ("pores") and rock fissures.[3] *Permeability* is a soil property describing the rate at which groundwater is transmitted through a soil. Due to their larger grain sizes, gravels and sands are much more permeable than silts and clays, and therefore drain more quickly.[4]

Subsurface Stress

Subsurface stresses in soil can be carried by both solid particles and pore water. *Effective stress* is the portion of the total stress carried by the solid particles. The effective stress in a soil is computed using the equation $\sigma' = \sigma - u$, where σ' = the effective stress, σ = the total stress, and u = the pore water pressure of the groundwater. Given this relationship, it is clear that effective stress decreases as the pore water pressure increases. Thus, the presence of groundwater reduces the effective stress in a soil. Effective stress is consequently affected by factors which influence groundwater such as rainfall, pumping practices, and irrigation activities. Furthermore, effective stress governs soil behavior and—perhaps most importantly—the shear strength of a soil.[5]

Settlement

Settlement is defined as the downward movement of soil due to induced vertical stresses. *Subsidence* is a term used to describe settlement that occurs over a large area. Settlement is induced in a soil whenever the vertical effective stress in that soil increases. In general, clays and silts experience larger amounts of settlement than sands and gravels, and this settlement occurs over a longer period of time.[6]

Shear Strength

The *shear strength* of a soil is the greatest shear stress which the soil can sustain without failure. Shear stresses in soils are resisted by the interactions between the soil particles, primarily the rearrangement of those particles when sustaining stress. Using the Mohr-Coulomb failure criterion, which is the most common failure theory assumed for soil, the shear strength is defined by the equation $s = c' + \sigma' \tan\phi'$, where s = shear strength, c' = effective cohesion, σ' = effective stress on the failure plane, and ϕ' = effective friction angle. A soil's shear strength is therefore linearly related to its effective stress. When the applied shear stress exceeds the shear strength of that soil, the soil can no longer support the loading and failure occurs.[7]

Failures can also occur due to the effects of groundwater. The *hydraulic gradient* is a ratio of the change in the total head (energy) of flowing water to a unit length in the direction of flow. Mathematically, the hydraulic gradient is defined as $i = \Delta h/\Delta l$, where $i =$ the hydraulic gradient of the soil, $h =$ the total head, and $l =$ the distance the water travels.[8] The critical hydraulic gradient for water flowing through soil is defined as $i_{cr} = (\gamma_{sat} - \gamma_w)/\gamma_w$, where $i_{cr} =$ the critical hydraulic gradient, $\gamma_{sat} =$ the saturated unit weight of the soil, and $\gamma_w =$ the unit weight of water. The critical hydraulic gradient represents a state of zero effective stress (σ' = 0), which corresponds to zero shear strength in cohesionless soils. This indicates incipient failure.[9]

In the design of structures located adjacent to bodies of water, knowing the critical hydraulic gradient of the underlying soil is crucial to understanding the potential for a soil failure. Underseepage is a form of groundwater motion that often precedes failure. When foundation soils underlying an earth structure such as a levee are sufficiently permeable, water may travel rapidly under the structure, thereby significantly increasing the pore pressure. The resulting reductions in effective stress and shear strength can initiate catastrophic instability, potentially resulting in piping failure. Piping failure occurs when seeping water erodes and removes soil, beginning from the exit point of the seepage path and advancing beneath the earth structure.[10] This process forms an enclosed, pipe-like channel through which water and eroded material may flow unimpeded. The occurrence of this phenomenon beneath a levee can be predicted by comparing the critical hydraulic gradient to the vertical exit gradient at the toe of the structure.[11] If the exit gradient is sufficiently raised due to the occurrence of underseepage, then there remains little resistance to soil erosion and piping ensues.[12]

Hurricane Katrina: Disaster

Overview

On August 29, 2005, Hurricane Katrina made landfall as a Category 3 storm southeast of the city of New Orleans, LA.[13] The effects of wind-driven waves, high tide, precipitation, and reduced local atmospheric pressure resulted in storm surges ranging from 15 to 20 feet in the Gulf of Mexico and Lake Borgne to the east, and from 10 to 14 feet along the southern shore of Lake Pontchartrain to the north of New Orleans.[14] Levee breaches occurred at fifty locations along the city's hurricane protection system, resulting in significant flooding of approximately 80 percent of the city.[15] The storm was directly responsible for 1,200 fatalities and caused an estimated $108 billion in property damage.[16]

The catastrophic failure of the New Orleans hurricane protection system raised numerous questions regarding the underlying engineering and management practices employed in the development of the system. Several organizations conducted investigations, producing substantial evidence of poor engineering judgment and practice, disorganization of the construction and implementation of system components, and a failure to appreciate the risk to life and property should the system fail.

Levees and Floodwalls in New Orleans

The New Orleans Flood Defense System (NOFDS) is an approximately 350-mile-long system composed predominantly of federally constructed and locally managed levees, floodwalls, and pumping stations that protect a series of separate basins.[17] The largest elements of this network were developed by the US Army Corps of Engineers (USACE) following Hurricane Betsy in 1965[18] and are often referred to as the Hurricane Protection System (HPS). The majority of the system is composed of earthen levees.[19] Prior to Hurricane Katrina, Hurricane Betsy was one of the most devastating hurricanes to affect New Orleans. The storm resulted in 75 deaths and over $1 billion in damage across southeast Louisiana and Florida, and caused catastrophic flooding in New Orleans' Lower Ninth Ward.[20] The purpose of the HPS was to prevent similar catastrophic flooding during future storms (such as Katrina).

Levees prevent the flow of water into populated or otherwise vulnerable areas by acting as a barrier against rising water and storm surge activity. After Hurricane Betsy, pre-existing levees were heightened to prevent flooding and maintain canal capacity.[21] Traditionally, the heightening of a levee is achieved through the addition of compacted material to the land side of the levee, which heightens the levee and increases the width of the levee's base.[22] Residential development alongside the existing levees, combined with the anticipated cost of compensating and removing residents, inhibited the implementation of the traditional heightening method. Consequently, the USACE pursued the construction of floodwalls atop the existing levees. These floodwalls—comprised of concrete walls supported by steel sheet piles driven into the existing earth levees—would provide additional height without widening the base of the levee.[23]

Three different styles of floodwalls were used, each named for its cross-sectional shape. *T-walls*, named for the similarity between their cross-sectional shape and an inverted letter "T", were supported by continuous steel sheet-pile walls extending from the above-ground concrete portion of the structure down into the earth below the levee, thereby reducing seepage beneath the wall. The T-walls were additionally supported by precast concrete or steel H-piles driven into the earth below. A slightly modified version of the T-wall, known as an *L-wall* due to its cross-sectional shape, was implemented in very limited quantities. *I-walls*, named for the similarity between their cross-sectional shape and the letter "I", were supported by continuous steel sheet-pile walls identical to those used for the T-walls. Unlike the T-walls, however, the I-walls did not include deep pile foundations to anchor the walls more strongly in place. The overwhelming majority of the floodwalls in the NOFDS/HPS were these simpler I-walls.[24]

Levee Failures during Hurricane Katrina

The floodwalls were put to the test when Hurricane Katrina made landfall. Levee breaches occurred at fifty locations along the HPS, forty-six of which were the result of the overtopping and subsequent erosion of the levees. The remaining four failures were the result of dramatic floodwall foundation failures along the 17th Street Canal, the Inner Harbor Navigation Canal (IHNC), and at two points along the London Avenue Canal. In addition to the breaches, approximately 220 miles of the levees and floodwalls experienced some sort of damage.[25]

Hurricane Katrina in the Curriculum

Implementation at Merrimack College

The curricular concepts for geotechnical engineering are well illustrated by the failure of the New Orleans levee system during Hurricane Katrina. In *Civil Engineering 3020 –*

Geotechnical Engineering at Merrimack College, Hurricane Katrina serves as an overarching theme throughout the entire semester. The first class of the semester is a case study of Hurricane Katrina which introduces students to the events leading up to Hurricane Katrina (including the history of the levee system); the mechanics behind the levee failures; and the failures in engineering, construction, maintenance, and public policy that ultimately contributed to the levee breaches. The students' first course assignment is to write a brief essay on some aspect of the disaster, focusing either on the past, the present (during the disaster), or the future, for example:

- The past: The pre-existing geological/geotechnical conditions that made New Orleans susceptible to hurricane devastation or the public policy decisions that contributed to New Orleans' vulnerability
- The present: Why specific levee failures occurred during Hurricane Katrina
- The future: How the levees and hurricane protection system are being improved to protect New Orleans in the future.

During the semester, when new course topics are addressed, these topics are linked to the Hurricane Katrina levee failures. Once students understand the significance of the course content, they are more able to retain and appreciate the material. During the final class meeting of the semester, students reflect upon Hurricane Katrina through the lens of soil mechanics and geotechnical engineering, using the concepts learned throughout the semester. Hurricane Katrina serves as a poignant, real-world example of the importance of geotechnical engineering and the consequences of failure. In this section, specific recommendations are provided on how various aspects of the levee failures during Hurricane Katrina can be incorporated into courses in geotechnical engineering and related topics.

Importance of Engineering Geology

The performance of the HPS was heavily dependent upon the engineering properties of the underlying soils. To understand the engineering properties of the soils underlying the levees and floodwalls protecting New Orleans, knowledge of the geologic history of the area is required. New Orleans is located within the Mississippi River deltaic plain. River and lake activity have resulted in large quantities of fine-grained silts, clays and organic materials, with 90 percent (excluding artificially filled areas) of New Orleans being underlain by swamp or marsh deposits.[26] One of the broad themes underlying the failures described in this chapter—and in many other geotechnical engineering failures throughout history—is the disconnect between engineering geology and geotechnical engineering. The geologic conditions under which soil is formed and deposited will ultimately influence how this soil behaves when subjected to loads.

Overtopping and Erosion Failures: Linkage to Soil Classification and Compaction

The levee failures underlie the importance of proper soil classification: some soil types should be avoided in certain applications. Levees with a core constructed of well-compacted, low-permeability clay are typically more resistant to erosion than those constructed using coarse-grained soils (such as sands), which are susceptible to erosion.[27] Unfortunately, the use of erosion-susceptible soils as levee material was inexplicably common along some portions of the system. Some levees were composed primarily of material dredged from nearby waterways—a process known as hydraulic filling—that often consisted of erodible, lightweight sands that were poorly compacted.[28] Exacerbating the usage of inappropriate soils in levee construction, most of the levee system did not incorporate any form of protection against overtopping or erosion along the land-sides of levees.[29] Relatively inexpensive measures, such as concrete splash-pads, could have been incorporated into the design to reduce erosion resulting from overtopping. Similarly, this erosion could have been reduced by using T-walls—which incorporate a horizontal concrete slab behind the vertical portion of the wall—more extensively, rather than opting for the less expensive, completely vertical I-walls.[30] The general lack of resilience to overtopping and erosion significantly increased the volume of flooding and the resulting devastation.[31] The selection of poor levee material and the general lack of system resiliency exemplify the tradeoff between technical adequacy and financial cost inherent in many engineering projects.

Settlement

Prior to Hurricane Katrina, the city of New Orleans was already an excellent case study for concepts involving settlement. The reasons that large areas of New Orleans lie below sea level can be explained by geotechnical engineering principles. Subsidence, combined with the slow rise in sea level, has left large portions of the city currently below sea level elevation.[32] This renders the city increasingly vulnerable to tropical storm events, particularly to flooding associated with a breaching of the levee system.[33] Several factors have led to the large-scale settlement occurring around New Orleans. Increases in the effective stress in the underlying soils—caused by structural loadings and by the pumping of groundwater—produces settlement. The slow drainage rates of the clays in the area result in persistent long-term settlement, which is exacerbated by the decomposition of organic matter. Furthermore, tectonic activity also contributes to the subsidence of the entire Gulf Coast region, including New Orleans.[34]

To accurately determine the elevations—relative to sea level—necessary to design and construct a flood protection system, the accuracy of the referenced benchmark datum is critical. When many of the floodwalls surrounding New Orleans were constructed, outdated variations of the NGVD29 datum, which is based on terrestrial reference points rather than on mean sea level, were referenced. The decision to use terrestrial benchmarks completely neglected the effects of subsidence and sea level rise on ground elevation. Therefore, the floodwalls were constructed to a lower protection height relative to sea level than originally mandated and authorized by Congress.[35] This led to an increase in overtopping during Katrina, and consequently contributed to the erosion-induced breaching of floodwalls and levees.[36] For example, the I-walls constructed along the 17th Street Canal levees in the 1990s were intended to extend 14.0 feet above sea level. Currently, these floodwalls lie 1.3 to 1.9 feet below that design elevation.[37] The peak storm surges caused by Katrina were commonly between 1 to 3 feet above the tops of the existing levees and floodwalls, only slightly exceeding the intended design elevation of those structures. If the levees and floodwalls had been constructed to the proper elevations, fewer overtopping-induced failures might have occurred.[38]

Groundwater Flow

All of the four non-overtopping floodwall and levee foundation failures occurred without water levels reaching their design elevations.[39] The causes have been determined to consist of underseepage and piping, the development of a water-filled gap between the I-wall and the earth material of the surrounding levee, and the development of slip surfaces along weak strata in the soils beneath the levees.[40]

Underseepage played a role in the two breaches of levees along the London Avenue Canal. The I-walls of the levees were laterally supported solely by the cantilever action of their supporting steel sheet pile walls being embedded in the earth levees. Hydrostatic pressure due to rising water levels caused the portion of the I-wall atop the levees to deflect backwards (towards the land side), exposing the sheet piles and allowing water to fill the widening space.

The gap widened until the water extended downward to the bottom tip of the sheet piles, allowing for water to flow more easily beneath the levee.[41] The groundwater exerted too large of a hydraulic gradient for the soil to remain intact, initiating piping failure. The formation of a water-filled gap was not considered in the design of the levees despite the development of a similar gap during a 1985 I-wall test conducted by the USACE.[42] The likelihood of an underseepage-related failure was therefore inaccurately calculated and mistakenly ignored. This design omission underscores the importance of considering all possible failure modes in engineering design, an important concept for students to appreciate.

Shear Strength Failure

With the formation of the water-filled gap, the length of the surface providing shearing resistance against backwards lateral translation was reduced, significantly increasing the potential for a shearing failure. This reduction in resisting forces is likely to have caused the lateral translation of the 17th Street Canal levee and floodwall.[43] The critical layer for the 17th Street Canal failure was a stratum of weak organic soil: the applied stresses exceeded the shear strengths of this layer, resulting in a catastrophic failure of the soil. This thin layer was composed of organic clayey silt and was discovered at varying depths between 8.3 and 11 feet below the ground surface in borings made under the supervision of the Independent Levee Investigation Team (ILIT) after Katrina. The water content for the layer was in excess of 270 percent, and physical evidence indicated that extremely high pore pressures likely developed as a result. This significantly reduced the shear strength along the layer, leading to the lateral translation and failure of the levee.[44] This layer had remained undetected despite drilling conducted during the construction of the levees prior to Katrina. The ILIT report deemed the failure to detect this layer to be the result of those drillings having been conducted without the supervision of an expert geological engineer with knowledge of the site's complexity and experience in detecting and analyzing such layers.[45] The failure of the 17th Street Canal levee can be incorporated in numerous course lessons throughout the semester, such as engineering geology, physical soil properties (and the implications of high water content), subsurface explorations, and shear strength.

The USACE also overestimated the strength of the foundation soils beneath and surrounding the levees. Directly beneath the centerline of a levee embankment, foundation soils experience greater effective stress due to the weight of the overlying levee material, and therefore exhibit greater shear strengths. The soils beneath the toe of a levee, however, are weaker because they are not subjected to the same amount of effective stress. During the design of the levees, tests were performed only on the soil directly beneath the centerline of the embankment, and shear strengths were estimated based on those tests. The strength of the soils outside the centerline of the levee and specifically along the toe—arguably the most critical point of the structure—were overestimated as a result. Furthermore, the factor of safety (FS) used for the design was only 1.3, an outdated figure originally selected for the design of levees providing protection for non-populous agricultural areas.[46] The target factor of safety was not reflective of the risk to human life posed by a potential failure of the levee system during a hurricane event; USACE standards call for target factors of safety of at least 1.4 to 1.5.[47] Overestimation of shear strength and usage of low factors of safety are unconservative practices that can lead to engineering failures, and this case study teaches students the importance of reasonable conservatism in engineering design.

The Oso, Washington, Landslide

On March 22, 2014, an unstable slope east of Oso, Washington, catastrophically failed, resulting in the movement of approximately 7.6 million cubic yards of earth. Forty-three people were killed in the landslide, which now has the distinction of being the deadliest single landslide in American history. The landslide reached distances of 0.6 miles from the toe of the slope, destroying approximately fifty homes and other structures and temporarily damming the North Fork of the Stillaguamish River.[48] Like Hurricane Katrina, the Oso landslide illustrates a number of concepts that are taught in geotechnical engineering courses. Some of these concepts are briefly discussed in this section.

First, this disaster serves as an excellent example of the influence of groundwater on subsurface stresses and shear strengths. The 2014 slide took place along the edge of a plateau composed of glacially deposited sands on top of lake-deposited silts and clays.[49] In March 2014, Oso received near-record amounts of precipitation. The entire season had been especially wet, with precipitation in the area between February and March at 150–200 percent of the long-term average.[50] The sands at the site are very permeable, much more so than the underlying silts and clays. Thus, groundwater at the site drains through the sand layer, but the very low permeability of the saturated silts and clays beneath the sand causes groundwater to collect in the overlying sand.[51] When soil is saturated, the pore water reduces interlocking and shearing between the soil particles, which in turn reduces the soil's frictional strength (the primary source of strength in sands). The majority of the rainfall was most likely retained within the glacial sand layer along the top of the slope. The corresponding reduction in effective stress and soil strength was likely to have been a significant factor in the initiation of the slide.

The proximity of the Stillaguamish River to the toe of the hill was likely to have been another contributing factor for the landslide. Miller and Miller[52] concluded that there was a strong tendency for the Stillaguamish to preserve its position at the base of the slope, which results in regular slumping into the river. These gradual changes in geometry at the base of the slope ultimately reduce the stability of the entire slide mass, thereby increasing the potential for a large catastrophic failure.[53] The combination of soils present, historical geologic and groundwater activity, and previous slide activity should have served as a clear indicator that the area was at risk for further landslides.

In addition to the geological aspects of the disaster, policy decisions regarding land use in the Oso area have come under increased scrutiny. The permitting of residential development downslope of the Hazel slide, in spite of the site's history of landslides, has been widely questioned, as this ultimately placed more people in the path of the deadly landslide. Revelations of logging activity in the area (particularly behind the hill that failed) have raised questions regarding how effectively logging restrictions were enforced; logging in any area prone to landslide activity has been a point of engineering concern and is associated with a risk of increased groundwater recharge and consequent reduction of slope stability.[54]

There were many opportunities to learn from past failures in the Oso area; studies detailed the volatile combination of soil and groundwater conditions present at the site,[55] but the warning signs were not sufficiently acted upon. Prior to the catastrophic 2014 landslide, this specific hillside had experienced slope failures in 1949, 1951, 1964, 1967, 1988, and most recently (prior to the 2014 event) in 2006, when 300 yards of the hillside slid into—and temporarily dammed—the Stillaguamish River. Formal assessments for the probability of further landslide activity in the area were either never performed or never published.[56] Like Hurricane Betsy in New Orleans, the past landslides at Oso represented learning opportunities that were either missed or ignored. The Oso landslide, like Hurricane Katrina, serves as an important lesson for engineering students about the importance of engineering history and learning from the past.

Conclusions

The levee failures during Hurricane Katrina were one of the largest failures of a civil engineering system in American history. The inadequacies of the levee system, and the examples of its poor performance during Hurricane Katrina, are numerous. However, key failures in the engineering of the system illustrate the importance and relevance of fundamental geotechnical engineering concepts. The use of outdated and inappropriate data, the utilization of erodible material in the construction of levees, the lack of protection against overtopping, and the failure to design against underseepage make it apparent that poor engineering judgment is substantially to blame for the disastrous consequences of Hurricane Katrina. In simulations that modeled the effects of Hurricane Katrina for a scenario in which the floodwalls did not catastrophically fail and the pumping stations remained functional, the results indicated that nearly two-thirds of the deaths and more than half the property losses would not have occurred.[57]

Undergraduate civil engineering students represent the next generation of engineering professionals and will be responsible for addressing these types of disasters in the future. Events such as Hurricane Katrina and the Oso landslide provide real-world examples of concepts already being taught in undergraduate curricula. Incorporating natural disasters into the curriculum provides student engineers with a keener awareness of the impacts of engineering decisions and the applicability of technical concepts to real-world events. These curricular bridges highlight the importance and relevance of soil mechanics concepts such as soil classification, groundwater flow, settlement, subsurface stress, shear strength, and soil failures, as well as the broader implications of errors in design, maintenance, and public policy. Educating student engineers on the failures of the past is vital to preventing failures of this magnitude from occurring in the future, and in the wake of disasters such as Hurricane Katrina and the Oso landslide, preventing such events should be every engineer's priority.

Notes

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