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Application of an alluvial architecture model to better understand seepage risk in floodplains

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ABSTRACT

The amount and distribution of coarse-grained sediment (e.g., sands and gravels) relative to fine-grained sediment (e.g., clays and silts) within a floodplain influences many of the floodplain geotechnical properties, including the potential for groundwater seepage. Seepage is a primary driver of levee and dam failure, and understanding its potential is of paramount concern to engineers and resource managers. This paper reports the results of a computational modeling study that simulated alluvial floodplain construction using a suite of simple geomorphic process-imitating rules.

A model aggrades a floodplain cross section within an alluvial basin, creating floodplain architecture by differentiating between sediment deposited by channel processes (sand) and sediment deposited by overbank flood processes (clay). The evolution of two floodplain cross sections of the Trinity River, near Dallas, Texas is simulated using five different experimental scenarios. The study area is the site of large levee rehabilitation projects in which accurate characterization of the geologic environment has significant engineering importance. Study results predict that scenario components including the alluvial basin width, the initial topography of the floodplain base level, and the channel aggradation rate significantly affect the fraction of the floodplain width that contains channel deposits by influencing the avulsion frequency of the river during floodplain construction. Increased avulsion frequency equated to more numerous, yet smaller channel deposits. The dimensions of the channel deposits predicted by this study are similar to those typically observed in large, fully meandering river systems. The model devised for this study is relatively simple and can be run in multiple iterations to produce probabilistic outputs, such as the likely range of channel deposit widths within a floodplain cross section. This type of information is useful to engineers for a host of applications including predicting the data collection density necessary to characterize the geotechnical properties of a project site.

1. Introduction

The alluvial architecture of a floodplain refers to the lithology and spatial distribution of the sedimentary facies that compose the floodplain subsurface (Allan, 1978; Shanley and McCabe, 1993). The character of the alluvial architecture plays an important role in determining the geotechnical properties within the floodplain, such as areas of high and low fluid seepage potential (Webb and Davis, 1998; Willis and Tang, 2010; Li and Caers, 2011). Relatively coarse-grained architectural elements, such as sand or gravel sedimentary deposits, are porous and can serve as effective reservoirs of underground fluid, such as water and hydrocarbon. Also, coarse-grained deposits have relatively high hydraulic conductivities and can serve as efficient seepage conduits. Because of these properties, it is often necessary to understand the alluvial architecture of an area to properly construct and maintain engineering structures that might become adversely affected by subsurface seepage, such as dams or levees (May and Schmitz, 1996). Identifying floodplain areas with high seepage potential due to the underlying lithology (i.e., coarse-grained sediment deposits) offers engineers the opportunity to modify project plans and take precautions to reduce the probability that the engineered structure will become adversely impacted from seepage.

The alluvial architecture of an individual floodplain is difficult to define precisely because of the large volume of floodplain material involved, the architectural elements occur in a wide range of sizes, and most of the elements occur in the subsurface and are not directly measurable (Collinson, 1978; Allen, 1979; Koltermann and Gorelick, 1996). However, the distribution of the sedimentary deposits composing a floodplain is primarily an artifact of the fundamental fluvial processes active within the floodplain through time (Blakey and Gubitosa, 1984; Mohrig et al., 2000; Tye, 2004; Peakall et al., 2007). Therefore, identifying these processes, which are relatively well understood, and the manner in which the processes operate within a specific floodplain can provide valuable information on how sediment is locally distributed over time (Hajek and Wolinsky, 2012).

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For most fluvial systems, stationary sediment that is exposed to fluvial flow is entrained dependent on [1] the relative force of the flow exerted on the sedimentary material and [2] the inertial force that controls the material's resistance to entrainment, which typically increases with the grain size and the cohesion of the material (Bagnold, 1956; Leopold et al., 1964; Dietrich and Smith, 1984). If the fluid force is greater than the inertial force, the sedimentary material is entrained by the flow and transported downstream. The balance of those two forces, in addition to the pre-existing, external material composing the environment containing them (e.g., the underlying rock in an incising system), controls much of the composition and organization of the river basin and its floodplain (Schumm, 1968). In an actively building (aggrading) floodplain within an alluvial basin, the river channel is composed of sediment deposited by flowing water within the channel banks. The associated floodplain is primarily composed of sediment transported and deposited by unchannelized water, typically by overbank floodwater. These two types of flow and their associated sedimentation regimes are responsible for the first-order organization of the architecture for most aggrading floodplains (Fielding, 1986; Paola, 2000). Sediment transport capacity and competency, which set the amount and maximum grain size of sediment transport, are exponentially related to the magnitude of force exerted by flow. Generally, unchannelized flow over the floodplain produces lower tractive forces than that occurring within the channel system. This phenomenon creates a spatial disparity in relative sediment grain size within the drainage basin, as fine-grained sediment becomes deposited upon the floodplain surface and relatively coarse-grained sediment becomes deposited within the channel network itself (Allan, 1974; Friend et al., 1979; Fielding, 1986). As the floodplain aggrades, it becomes filled with two significantly different types of deposits: fine-grained floodplain deposits composed of clays and silts and coarse-grained channel deposits composed of sands and gravels (assuming this range of grain sizes is present within the fluvial system). These two deposit types compose the alluvial architecture of interest for this study.

In this study, we examine the fundamental geomorphic processes responsible for the distribution of coarse and fine sediment within a floodplain. We employ a computational alluvial architecture model to quantify how different processes (e.g., lateral channel migration, floodplain sedimentation, avulsion) might alter floodplain development. By identifying how these processes affect the alluvial architecture of the floodplain, we propose that it becomes possible to predict characteristics of the alluvial architecture, including those with engineering significance. Alluvial architecture-type models have been successfully applied to identify the influence of geomorphic parameters and processes on the distribution of coarse-grained sediment deposits relative to finer-grained deposits, but few studies have attempted to use the modeling results outside of reservoir engineering and management applications (see North (1996), Bridge (2008), and Hajek and Wolinsky (2012) for eloquent reviews of alluvial architecture modeling). Alluvial architecture models explore how channel geometry, channel avulsion frequency, floodplain sedimentation rate, and uplift/subsidence affect the density of channel deposits within a floodplain cross section (Allen, 1979; Bridge and Leeder, 1979; Mackey and Bridge, 1995; Leeder et al., 1996; Gross and Small, 1998; Tornqvist and Bridge, 2002; Jerolmack and Paola, 2007; Willis and Tang, 2010). They also help define the amount of dependence that the geomorphic parameters typically have on each other (such as sedimentation rate and avulsion frequency) (Bryant et al., 1995; Heller and Paola, 1996).

The objectives of this study are: [1] to examine how the magnitudes of specific geomorphic processes affect the alluvial architecture of a floodplain cross section with focus on the distribution of channel deposits (i.e.,sand) within the cross section, and [2] to explore how the results of a computational alluvial architecture model can aid a geotechnical investigation for an engineering project.

We initially calibrate our model with data collected from a geological investigation in support of a levee-engineering project and validate our model results against the investigation's observations. We employ an additional range of model input parameters, beyond that observed in the project area, to better identify how fluctuation of these parameters can affect the dimensions and distributions of the channel deposits within modeled floodplain cross sections.

2. Study site

This study employs hydrologic, geologic, and topographic data collected from the upper Trinity River drainage basin near Dallas, Texas (Figure 1). These data are used to calibrate the model boundary conditions and initial parameters, as well as validate the model output. The Trinity River floodplain near Dallas is the site of multiple civil-works levee construction and rehabilitation projects, some of which date back to the early 20th century (Roig-Silva et al., 2010). The types and densities of geologic data collected for these projects illustrate the typical data demand, availability, and collection procedures common to modern infrastructure engineering projects.

The Trinity River at Dallas drains an area of approximately 15,800 km^2. The city of Dallas lies immediately downstream of the confluence of the Elm Fork and the West Fork of the Trinity River system. Three distinct quaternary terraces have been identified surrounding the modern floodplain. The lowest and youngest of these terraces (formed 30 to 76 ka BP and referred to as the Hickory Creek Terrace) lies approximately 20 to 30 m above the modern floodplain at its location near Dallas (Ferring, 1990). The north and south faces of the lowest terrace are well matched in this area and range from being approximately 6-km apart at the upstream reach of the study area to being 1.5-km apart at the downstream extent of the study area. Municipal surface-water reservoirs were installed on both upstream tributaries of the Trinity River in the 1960s. Pre-1960 discharges for the 2-, 10-, and 50-year floods were 602, 1926, and 3943 m^3 s^{-1}, respectively. Post-1960 discharges for the 2-, 10,- and 50-year floods have been reduced to 594, 1337, 2105 m^3 s^{-1} , respectively.

The modern Trinity River levee system was built in response to the initiation of the Dallas Floodway project in the 1920s. The floodway project led to the eventual realignment of the Trinity River channel system to a parallel route approximately south of its natural course. A length of 36.4 km of 10-m tall levees surrounds the current channel system, constraining it to a 0.5–1.0-km wide floodplain. Before levee systems were in place, anecdotal evidence described large floods that inundated the full basin floor between the Hickory Creek terraces (Tompkins et al., 2010).

Geologic and geotechnical investigations carried out in support of the various Dallas Floodway projects have collected and synthesized more than 2000 geologic borings for the project area. However, the vast majority of the borings are limited to the area immediately surrounding the levee system (which approximates one-third to one-half of the modern floodplain width) and many borings are not deep enough to reach bedrock. Additional boring data from highway and bridge locations were analyzed for this study to better characterize the full basin width, which were provided by the Texas Department of Transportation. Boring data indicate that the bedrock (Cretaceous shale, chalk, and sandstone from the Eagle Ford and Austin Chalk Formations) that underlies the modern floodplain sediments typically lies between 5 to 20 m below the floodplain surface, dipping to the downstream (southeast) direction. Aerial imagery and topographic maps for the period preceding the channel realignment were collected and geo-referenced to identify the natural river channel planform. Within the study area, the modern Trinity River appeared to be of moderate sinuosity (1.5 to 1.7) with channel widths of 50 to 70 m and average meander amplitude near 800 m.