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Estimating the position and variability of buried bedrock surfaces in the St. Louis metro area

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ABSTRACT

The precise position of bedrock surface is the most important variable for evaluating seismic site response. The subsurface data suggest that the bedrock elevations in the St. Louis area are proportional to ground surface elevation, and bedrock depths tend to thin in dissected, loess-covered uplands. Automated contour maps of the estimated bedrock depth or elevation are commonly constructed using geographical information systems (GIS) that employ various interpolation algorithms. In deeply incised terrain interpolation techniques often make erroneous predictions because they tend to under- or overestimate surfaces influenced by paleolandscapes, such as incised channels that are subsequently filled, or by employing single contour models across areas of differing geomorphic settings. This paper compares two different models for estimating dissected and/or eroded bedrock surfaces beneath the greater St. Louis area, which varies with the geomorphic setting. These models include: 1) the depth-to-bedrock derived from ordinary kriging, and, 2) bedrock elevations derived from cokriging. Cross-sections derived from the GIS programs suggest that the estimated depth-to-bedrock tend to simplify the actual situations because they assume near-constant thickness between data points, ignoring natural undulations caused by previous erosion. These simplified surfaces of depth-to-bedrock were adjusted by considering data, which does not pierce the bedrock interface. The estimated bedrock elevation does not conform to local topographic variations in rugged, hilly terrain, and tends to over-smooth the natural undulations caused by stream incision. In rugged, deeply incised terrain the interpolation of bedrock depths yields more realistic estimates of the buried bedrock surface than those derived from bedrock elevations. In the major Holocene floodplains, we developed a technique employing complex curve-fitting of channel cross-sections to produce more realistic estimations of the spatial variability of depth-to-bedrock within the deeply-incised channels.

1. Introduction

The thickness and character of the geologically-youthful, unconsolidated materials lying atop a stiff, lithified geologic formation are commonly referred to as the soil cap by seismologists, while the much older and increasingly dense formational material is referred to as bedrock. The cap of lower density material can serve to amplify or diminish seismic energy, depending on its physical properties and thickness. In some instances, the soil cap may include deeply weathered horizons developed upon the bedrock. For these reasons, the thickness and consistency of unconsolidated cap are of utmost import in estimating seismic site response, a key variable for engineers designing structures. Undulations, such as those caused by buried channels, valleys, natural depressions, or local sediment basins can serve to dramatically alter incoming seismic energy, creating hazardous situations (Borcherdt et al., 1991; Kramer, 1996; Haase et al., 2010). For example, sites underlain by thick accumulations (>14-m) of unconsolidated sediments appear to be more prone to magnification of long period ground motions than those with less surficial sediments in the St. Louis metropolitan area (Chung and Rogers, in press-b; Rogers et al., 2007).

Isopleth maps are often constructed to provide generalized predictions of buried bedrock surfaces by interpolating subsurface data gleaned from field observations, engineering boring logs, water wells, and geophysical interpretations. The precise mix of and reliability of such data varies significantly, from place-to-place. Prior to the advent of GIS technology, isopleth maps were usually prepared manually, based on available data, area experience, and an understanding of the geomorphic evolution of the study area. Over the past few decades there has been a gradual shift toward computational methods using software programs like the ESRI's ArcGIS or Golden Software's SURFER. In rugged, hilly terrain interpolation techniques often necessitate erroneously smooth contouring of dissected bedrock surfaces, because: 1) contouring algorithms under- or overestimate bedrock surfaces in buried paleovalleys or entrenched and/or dissected terrain (common in loess-covered uplands), and, 2) a single contouring model across a contrasting geomorphic terrain often leads

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to inappropriate estimates (Hasenmueller, 2006; Nyquist et al., 1996).

A number of methods have been proposed to overcome problems associated with predicting the buried bedrock topography, interpolating bedrock surface elevations (BSE) or depth-to-bedrock (DTB) datasets. Nyquist et al. (1996) employed the cokriging technique that designated ground surface elevation as a secondary variable to predict the bedrock topography underlying the Oak Ridge, Tennessee, area. Gao et al. (2006) interpolated an initial bedrock surface using kriging, by employing an array of subsurface data penetrating the bedrock interface. They refined the initial approximation by repeating the interpolation using additional data that terminated above the bedrock interface, but extended beyond (deeper) the kriged bedrock surface, as it was initially interpolated.

Hasenmueller (2006) proposed a mapping method to subdivide Monroe County, Indiana, using relationships between the BSE and digital elevation models (DEM). The BSE was predicted in three subareas using different modeling techniques;

1) Independent bedrock surface model: This model was employed in areas where paleovalleys had been excavated into the bedrock without any physical correlation to the existing ground surface. The bedrock surface is initially approximated using data that pierces the bedrock interface, and then adjusted by considering data, which does not pierce the bedrock interface. This second approximation can be warped downward, depending on the geologic interpretations drawn from adjacent areas, or from local experience;
2) Dependent bedrock surface model: A dependent bedrock surface, sub-parallel to the existing ground surface, can be modeled by computing the relationship between the soil thickness and the structural trend of the existing ground surface;
3) Bedrock outcrop model: Thin residuum layers derived from weathering of bedrock or bedrock outcrops are assumed to be representative of surface elevations and can be replaced with the surface DEM values. These features area usually identified from the surficial geologic or soil maps.

Our study employed a two-pronged approach to estimating the topography of the buried bedrock surface beneath the St. Louis metro area, including: 1) depth-to-bedrock (DTB) model, and; 2) bedrock surface elevation (BSE) model, for hilly, dissected terrain, using geostatistical techniques. The results of these different approaches were then compared and evaluated. A polynomial regression curve-fitting method was then employed to produce a more realistic prediction of depth-to-bedrock in the floodplains.

2. Study area

The study area encompasses 33 7.5-minute quadrangles (1:24,000) in the greater St. Louis area, Missouri and Illinois. The St. Louis region contains the confluences of the Missouri, Illinois, and Meramec Rivers with the Mississippi River (Figure 1). The area is prone to the risk of earthquakes emanating from a number of seismic sources (McNulty and Obermeier, 1999; Cramer, 2001; Street et al., 2004; Obermeier et al., 2005; Petersen et al., 2008). The St. Louis area has an expected annualized earthquake loss of $58.5 million dollars (FEMA, 2008), based on its recent history of seismicity, which includes M5+ earthquakes every 20 years emanating from the Wabash Valley Seismic Zone and New Madrid Seismic Zone, which are located approximately 200 to 350 km from St. Louis.

2.1. Geologic setting

The topography of the buried bedrock surface underlying the St. Louis metro area appears to have been carved by glacial and fluvial processes during the pre-Illinois, Illinois, and Wisconsin glacial episodes (Goodfield, 1965; Allen and Ward, 1977; Grimley and Phillips, 2006). In the vicinity of the Mississippi–Missouri–Illinois confluences, ice dams formed during the late Pleistocene that resulted in short-term flow diversions (Goodfield, 1965) and temporary flow reversals (Elfrink and Siemens, 1998). The two dominant landforms produced by these processes are alluvial filled floodplains and dissected uplands covered by till and loess. The Quaternary glacial and postglacial sediments lie unconformably on dissected Paleozoic strata of Mississippian limestones and Pennsylvanian shales. Bedrock outcrops are limited to undercut river bluffs, road cuts, and rock quarries (Satterfield, 1977; Schultz, 1993; Grimley, 1999; Grimley, 2002; Grimley and Phillips, 2006). The regional orientation of the older

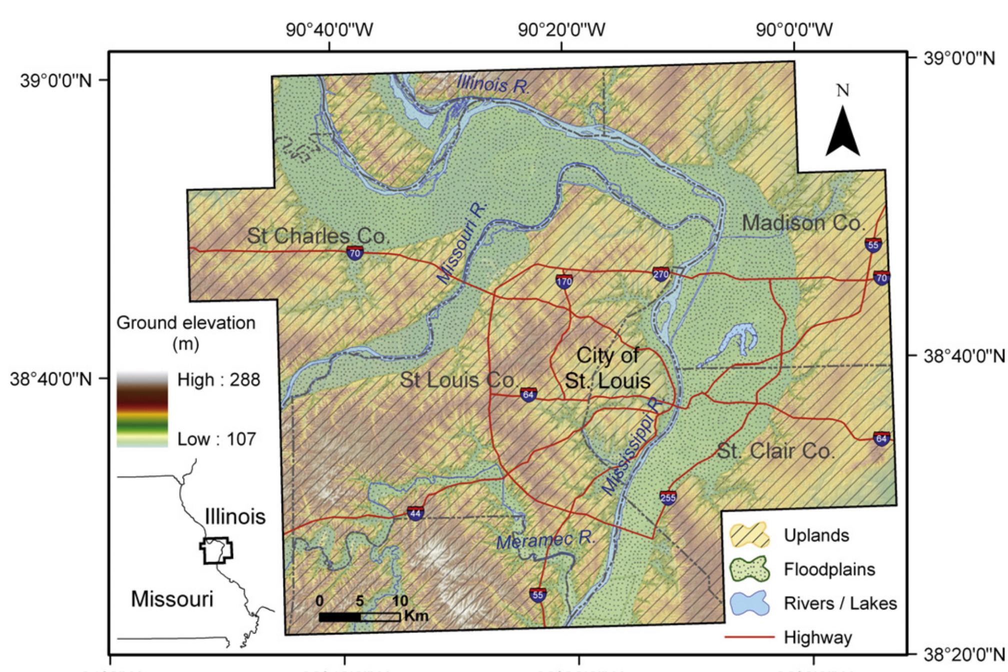

Fig. 1. Map of the metropolitan St. Louis study area showing regional topography and geomorphic settings of dissected loess-covered uplands and low-lying floodplains.