A MODIFIED DEM FOR REPRESENTING OVERHANGING TERRAIN

Michael B. Gousie, Hannah Lord

Wheaton College
Department of Computer Science
Norton, MA 02766, USA

ABSTRACT

We propose a modified Digital Elevation Model (DEM) that stores additional data to adequately represent overhanging terrain. The DEM contains one additional line in the header information that describes the encoding of the data for any overhanging structures, arches, or caves. This additional data is then appended to the end of the normal DEM file. We describe a procedural approach to render arches using this modified DEM. This procedure can thereby generate terrain from ground truth data as opposed to many current methods. The new DEM is backward compatible except for the one additional line in the header; it is also space efficient, needing minimal data necessary for representing the overhanging terrain, thus keeping the file size at $O(n^2)$.

***Index Terms*—** Terrain, digital elevation model, modeling, file format, overhangs.

1. INTRODUCTION

The digital elevation model (DEM), or the similar digital terrain model (DTM), is ubiquitous for storing two-dimensional heightfields in a regular grid. The USGS definition states that a DEM is a representation of the bare earth [1], which we assume here. DEMs are used in applications ranging from 3D terrain viewers, GIS in general, and commercial game engines. A DEM is a set of elevation values stored in a two-dimensional grid whose size is defined by means of header information that includes the number of rows and columns, among other spatial information. Such a data structure is both simple and space efficient at $O(n^2)$, where n is the larger of the row or column size. These traits are precisely what makes DEMs popular. However, their limitation is that only one elevation can be stored at each grid location. This restriction means that terrain structures with multiple vertical layers, such as overhanging cliffs, caves, or arches can not represented. We propose a modified DEM that removes this restriction while preserving the simplicity and space efficiency of the format. The modifications include an additional one-line description in the header information and data appended to the end of the original DEM. The data is only enough to adequately represent the overhanging structure and does not add significantly to the size of the file. Furthermore, because the additional data is appended to the end of the file, the DEM remains backward compatible to older systems except for amendments necessary to resolve the additional line in the header. Even this change can be avoided by placing the additional header line at the end of the traditional DEM file, then appending the data representing the overhang.

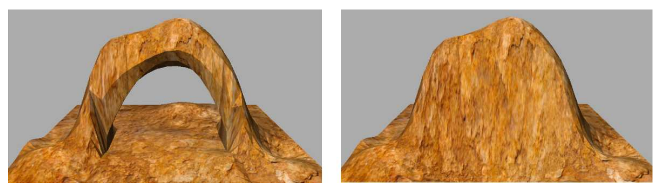

Fig. 1. Rendering of an arch (L) using our modified DEM compared with one using the traditional file (R).

Once we have the modified DEM, we must construct the overhanging terrain. The method does not fall readily into common terrain reconstruction categories [2], the main difference being that our procedure starts with DEM data that can represent real-world terrain. In this paper, we focus on arches, although the modified DEM can support any kind of terrain with multiple layers of elevations. We present an algorithm that renders an arch (see Figure 1) using the modified DEM without the need of user interaction, the details of which can be found in Section 4.

2. RELATED WORK

There seems to be relatively little work done in using any kind of modified DEM/DTM to represent complex terrain. However, much work has been done to represent and/or model terrain, including overhanging structures [2]. However, many of these are more concerned with showing realistic renderings of simulated, rather than real, arches.

Zang *et al.*[3] proposed a multi-layered tiled DEM. This could possibly represent overhanging structures, although their goal was to incorporate DEMs from multiple sources

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for the purposes of autonomous driving and city modeling. A hybrid approach by Peytavie *et al.* [4] suggested a framework for modeling complex terrain (which includes arches) in which one portion is a two-dimensional grid of material layer stacks. Solid height-map sets were proposed in [5]. Alonso and Solano [6] proposed the grounded heightmap tree. A standard heightmap is stored as the root node in a tree, and as overhanging structures are added, additional heightmaps are created and attached as nodes, yielding a hierarchy of elevations. Guo and Zhao [7] combined a DEM with a simplified point cloud, thus creating a true 3D model. They show that such a model can successfully describe an underground cave with relatively good space efficiency. Paris *et al.*[8] used implicit surfaces to represent and generate volumetric terrain.

A survey of many procedural generation methods was given by Smelik *et al.* [9]. Gamito and Musgrave [10] started with a $2\frac{1}{2}$D heightfield surface and then used a "terrain warping" technique computed by a differentiable vector field. Overhangs are constructed using a bicubic Bézier surface in [11]. Another volumetric procedural approach is used by Becher *et al.* [12] in which 3D curve-based primitives generate volumetric terrains.

3. THE MODIFIED DEM

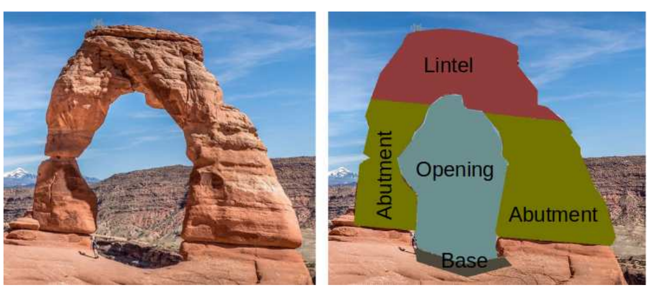

Fig. 2. Delicate Arch, Utah, at left, and the various components at right.

Terms for describing arches are not universal, so we define some here. Figure 2 shows a natural arch and its various components. The lintel is the structure that comprises the bridge between two abutments yielding an opening beneath. The base refers to the ground under the lintel. We refer to the sides of the arch along its length as the front and back "faces." The elevations of the upper surfaces of the lintel and the abutments are represented in a typical DEM; however, there is no data to describe the opening or the base. Hence, the arch is represented as a solid structure, as seen in Figure 1 (R).

Consider Figure 3, which shows one row of grid points along an arch. The highest portion of the lintel has an elevation of four units while the ground is at 0 (sea level). The blue triangles represent the regular grid points stored in a typical DEM; that is, only the elevations of the ground surrounding

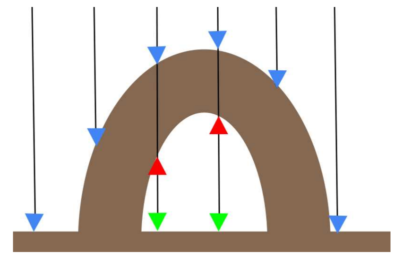

Fig. 3. Diagram of a simple structure showing the outer arch (blue), inner arch (red), and base (green) points along the DEM row/column.

the arch area, the top of the lintel, and the sloping abutments are captured by the format. All of this can be thought of as the *outer arch*. The red triangles represent the bottom of the lintel that *should* define the upper part of the arch opening (the *inner arch*). The green triangles represent the base. Neither of these latter two sets of values are captured in the DEM. We propose to modify a DEM in standard ESRI ASCII format [13] to incorporate this data.

An example of the header of a USGS DEM of Franconia, NH, in the ESRI format is as follows:

```
ncols         1773
nrows         1709
xllcorner     -71.72015765
yllcorner     44.02795833
cellsize      10
NODATA_value  -9999
```

where `ncols` and `nrows` represent the number of rows and columns in the two-dimensional (regular) grid, the `xllcorner`, `yllcorner` represent the left (western) and southern (bottom) coordinates of the DEM, respectively, and the `cellsize` is obvious. Any value in the DEM that matches the `NODATA_value` indicates that grid location does not have a viable elevation associated with it. This header is then followed by 1709 rows of 1773 elevation values, where each cell is 10 meters square, thus comprising the regular grid.

Figure 4 shows a very small example DEM, which corresponds to the equally simple arch in Figure 3. As this is only a synthetic data file, the `xllcorner` and `yllcorner` are listed as 0 without loss of generality. To the normal six-line header we add an additional line of the form:

`multi` $rowSize$ $rowLocation$

where "multi" stands for "multiple elevations." The value $rowSize$ represents the number of additional rows needed to store each elevation set for the inner arch and the base. In this case, two rows are needed for the inner arch (shown in red) and base (shown in green). The $rowLocation$ value indicates the first row in the DEM (shown in blue) that matches the first row of the additional data; that is, the row that represents the outer arch that matches with the inner arch. Note that NODATA values are used for locations that are outside of the overhang area generally and the bottoms of the abutments specifically. Altogether, this format represents the "stacking" of the elevations along rows of the DEM, where the blue values represent the top of the arch (top of lintel) and the surrounding ground truth, the red represents the inner arch (underside of lintel), and the base represented by the green values, as shown in Figure 3.

```
ncols     6
nrows     7
xllcorner         0
yllcorner         0
cellsize 1
NODATA_value      -9999
multi     2       4
0         0       0       0       0       0
0         0       0       0.2     0.5     0
0         0       0       0       0       0
0         2       4       3       2       0
0         2.5     4       3.5     1.5     0
0         0.5     0.5     0       0       0
0         0       0       -9999   0       0
-9999     -9999   3       2       -9999   -9999
-9999     -9999   3       2       -9999   -9999
-9999     -9999   0       0       -9999   -9999
-9999     -9999   0       0       -9999   -9999
```

Fig. 4. Simple DEM in ESRI ASCII format of the arch shown in Figure 3. The areas indicated in yellow, red, and green comprise the additions to the DEM that model the arch.

One of the reasons the DEM is ubiquitous is its space efficiency along with its ease of use. Adding multiple elevations does not significantly impact the size of the original DEM; we are adding only enough data to represent the overhanging structure. Assuming $n = \texttt{max}(numRows, numCols)$, where $numRows$ and $numCols$ are the number of rows and columns in the DEM, the file has $O(n^2)$ space efficiency. The additional rows for any arches or overhangs will not exceed the original number of rows and no columns are added, so the space efficiency remains at $O(n^2)$.

4. RENDERING AN ARCH FROM MODIFIED DEM

While the format of the modified DEM is rather straightforward, the steps in creating a true three-dimensional surface is more complex. In this paper, we concentrate on rendering an arch; the ideas here can be extended to caves and general overhanging structures.

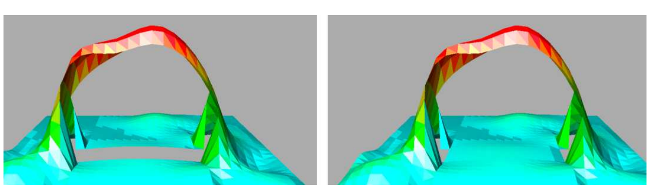

Fig. 5. Arch as stored in original DEM (L) and the upper arch with the base rendered (R).

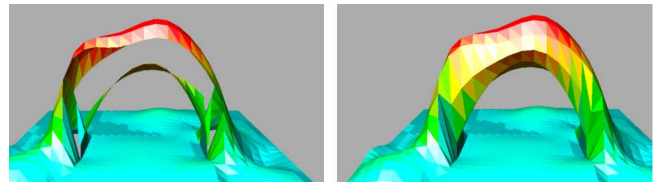

Fig. 6. The inside arch added (L) and the front and back faces of the lintel triangulated (R).

4.1. Modified DEM test data

There do not exist any DEMs of arches or any overhanging structures, as these can not be represented in the traditional format. We created a synthetic data file with additional arch data starting from a DEM of Zion National Park in Utah. This 30 meter resolution DEM includes the Kolob Arch. Using the general dimensions of this arch, taken from [14], as a rough guide, we created a small DEM of 25 rows and 26 columns with two sets of three rows representing the inner arch and the base. Note that this file is small because we are using just the area of the arch. The span of the arch is 287 feet (approx 87.5m), the thickness 75 feet (22.9m), and most importantly the width is 35 feet (10.7m). This means that the DEM with the 30 meter resolution can not adequately model this arch. Hence, we increased the resolution by doubling the number of rows and columns and interpolating. The additional `multi` arch data was then added to this file.

4.2. Rendering an arch

Starting with the aforementioned modified DEM, we create the initial ground-level layer, still as a regular grid. The multiple layers are then added systematically to represent arches and the like. This is done by adding a 3D mesh that is superimposed on the original DEM grid. By constraining the mesh points to the DEM grid, tessellation of the surface is relatively easy and computationally fast because it only entails triangulating the rectangular grid cells. The steps in the process of creating 3D terrain is as follows:

Read and store the DEM data: The 2D array data structures are constructed to store the multiple levels of heightmaps that describe the elevation layers needed to model the arch (refer back to Figure 3).

Triangulate the base and abutments: Figure 5 (L) shows the arch rendered with the outer arch as stored in the original DEM. The modified DEM defines the base, which is then triangulated to form the missing bottom of the arch in Figure 5 (R).

Triangulate and attach the inner arch: Triangulating the inner arch is straightforward, but it may be unclear as to where to attach it to rest of the structure. This is done by connecting the lower elevation of the inner arch to the closest base elevation, shown in Figure 6 (L).

Triangulate the faces: The sides of the arch must now be interpolated and triangulated to form a solid, three-dimensional surface. This is done easily by connecting the vertices of the outer arch with the matching vertices of the inner arch, yielding the surface shown in Figure 6 (R).

Render the final tessellation: Figure 1 shows the final rendering with applied textures compared to the arch represented as a solid block by a traditional DEM. Finally, Figure 7 shows another arch, this time in the context of a larger DEM that includes other features.

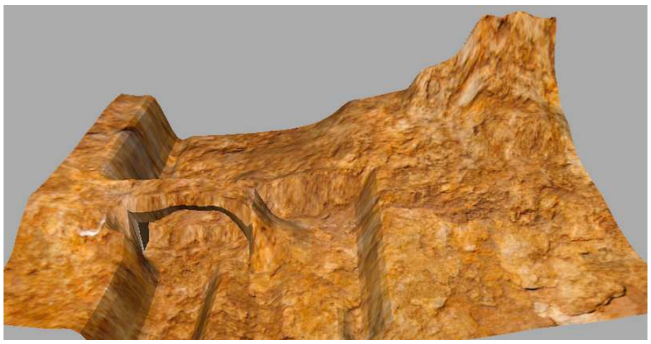

Fig. 7. An arch shown in a small canyon within a larger terrain surface.

5. CONCLUSIONS AND FUTURE WORK

We proposed a modified DEM that can store layers of elevation data so that overhanging terrain can be represented. The new format remains a simple two-dimensional data structure, albeit with one extra line in the header and additional rows that represent layers of the overhanging terrain. We then presented an algorithm for generating a three-dimensional model from the modified DEM. The algorithm entails storing the various layers of the overhanging structure and then tessellating via triangulation/interpolation of grid cells. Applying the algorithm to synthetic modified DEMs yielded realistic (to the degree the resolution permitted) three-dimensional arches. In the future, more testing with real-world data, as well as other kinds of overhanging terrain, is warranted.

6. REFERENCES

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