

TRIANGULATED DIGITAL ELEVATION MODEL: DEFINITION OF A NEW REPRESENTATION

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ABSTRACT

In this paper we discuss about the need of a new DEM representation for simulation in GIS. This leads us to analyse through quality criteria the current DEM structures. Then we propose a new DEM representation adapted for spatial and graph terrain analysis. An algorithm is presented and the qualities of this structure are analysed. Finally, this structure is used in a thematic application for analysis and protection against avalanches.

Keywords : DEM structure, DEM generation, TIN, regular network, DEM quality criterion, Delaunay triangulation, topographic constraints

1. INTRODUCTION : NEED OF A NEW REPRESENTATION ?

The increasing use of DEM (Digital Elevation Model), especially in GIS, highlights the compromise between two main issues: the quality of terrain modelling versus large data volume handling. For instance, the growing needs of environmental simulation requires high performance and flexible terrain models. In particular, we can cite the need of combining 3D detailed representation with dynamic terrain changes.

This situation brings us, in a first step, to elaborate quality specifications and validation methods for generation and exploitation. Those criteria are used to search the most adapted structure for simulation. The results leads us to introduce a new DEM representation. Finally, this structure is used in a thematic application : the avalanche path analysis.

Several quality rules are defined in order to compare and qualify the various digital models. They are based on four geometrical criteria which are validated in a relative or absolute way, using internal or external information.

2. DEM QUALITY AND VALIDATION:

We define quality criteria to compare the most current

DEM representations. Then, we present the different DEM validation methods.

Mesh quality : The mesh quality is linked to the quality of its elements. We define :

$$Q_M = \min_{e \in M} Q_e$$

2.1 the quality criteria :

the criteria are based on geometrical considerations at different orders in the mesh [5].

The zero order criteria : they work with the mesh vertices.

- The height accuracy: It is defined as the local height mean square error.
- The planimetric accuracy: It depends on the sensor accuracy and the data resampling method.

Theses values are easily calculated without being significant of the DEM global quality.

The first order criterion : it concerns the mesh elementary surface.

- The clinometric accuracy : in a DEM, the slope error is worst than the local zero order error. This is especially sensitive in applications using slopes as the natural risk management. The error can be measured by the intercorrelation of DEM contours and other source extracted contours. It can also be obtained by measuring the planimetric distortion and morphologic comparison (analysis of local extrema points).

The second order criterion : it is related to the mesh shape.

- The morphological realism : Because it is difficult to check the respect of terrain shape, we look at the similarity between the DEM texture and the modelled terrain texture. The DEM structural elements are analysed by sketching both DEM and real terrain. So we evaluate the intercorrelation between two networks of characteristic lines. This can be done using a low pass filter preserving the structures (low frequencies) and eliminating details (high frequencies).

2.2 DEM Validation:

The DEM is validated in two ways.

The relative validation just controls the internal DEM coherence without external information. We check that the DEM respects the basic topographic rules as for instance the rivers must flow in the good direction. We can for instance control the DEM hydrographic network in relation to the terrain structure. The problem of this internal validation is the detection and interpretation subjectivity of unrealistic shape : how to detect a real dam from an artificial one (for instance a bridge) without external information.

The absolute validation uses a reference to control the DEM. We want to compare measurements on DEM and on the reference. For instance we use ground control points, structural graphs (contour lines) or structuring graphs (road map, coast line). This step is used to calibrate the relative DEMs.

3. THE EXISTING REPRESENTATIONS :

The DEM can be represented as a continuous function (interpolation function) or as a mesh. A continuous approximation is difficult to obtain because of the terrain non stationarity. To take into account this problem, we look at the meshed structures.

There are two sorts of discrete representations : the regular grids and the irregular ones. We analyse their advantages and drawbacks through our quality criteria.

3.1 The regular grid DEM's:

It is the most classical representation. If a good accuracy for the mesh vertices is reachable, it is harder to respect the other quality criteria. The basic surface element (parallelepiped) gives an ambiguous slope approximation corrupts the clinometric accuracy.

The main drawback of this representation is the need to fix the sampling rate to the highest terrain frequency to obtain a good modelling (i.e. the sampling rate must be high enough to « see » all details). In that case, the data volume is prohibitive. Under this optimal value, the sampling rate can not take into account all the terrain structures and so the model inherits a poor morphological realism.

However, we must note that since we keep the rate and the orientation of sampling, this structure is easy to manipulate.

3.2 The TINs:

The TINs (Triangulated Irregular Networks) offer an interesting structure by proposing a triangle based

surface approximation. This modelling compensates some regular grid drawbacks without being a standard for simulation.

The triangular facet leads to a unique slope and so enhance the clinometric accuracy. This representation allows to include constraint lines (topologic structures) and the local point density adaptation. Those properties improve the DEM realism and the respect of the intrinsic frequencies of the modelled terrain.

Nevertheless, this graph doesn't possess any underlying spatial structure although it is based on the Delaunay triangulation. For that structure the Delaunay Triangulation is used as a fast triangulation algorithm without taking into account the induced properties of this graph. This drawback limits the operational abilities for the DEM surface exploitation (e.g. risk analysis). These remarks make this representation inadequate for simulation.

4. A NEW REPRESENTATION ?

After analysing the existing structures, we note :

- There is a cohabitation of two representation modes without a significant prevalence.
 - The DEM modelling and accuracy is often application dependant.
 - The model is a graph and not a spatial segmentation.
- So, we try to define a new representation taking into account these observations.

4.1 Philosophy:

Instead of applying a structure to the terrain (the regular sampling), we allow the terrain to structure the DEM. So, we adapt the data sampling to the type of landscape it represents and to the accuracy needed for the DEM application.

So, we look for a type of mesh, including the properties of both standard DEM plus the previous considerations. To keep the terrain structure, we warrant the presence of topographic lines in the mesh by using them as mesh constraints. We also want the ability for spatial reasoning which helps us to use the DEM as a set of regions. In that case, we can extend a measure done at a vertex to its whole influence region (for instance the soil roughness).

This leads us to propose a new structure: the Delaunay Constrained Triangulation (DCT).

4.2 Semantics :

It has to be stressed that the Delaunay **Constrained Triangulation** (DCT) is different from the Constrained Delaunay Triangulation (CDT). With the CDT, the constraints are introduced by exchanging the edges corresponding to the constraints. The corresponding triangulation loses the fundamental Delaunay geometrical properties. On the other hand, the DCT is a triangulation that keeps all the properties of the Delaunay triangulation such as the duality with the Dirichlet tessellation.

4.3 Algorithm :

4.3.1 Data :

The topographical data are considered to be a set of 3D scattered data including a set of topographical

constraint lines (watershed, talweg). Because these data may come from different sources, they are referenced in a unique system of reference.

The advantage of this data set is that it uses a small amount of points and an irregular (spatial) distribution. Thanks to this property the model can be refined for the most important area whereas regions of lower interest are more roughly described.

The constraints of the DEM match the intrinsic features of the modelled terrain :

- Natural topographical elements : watershed, talweg, coast line.
- Made structures : roads, railways.

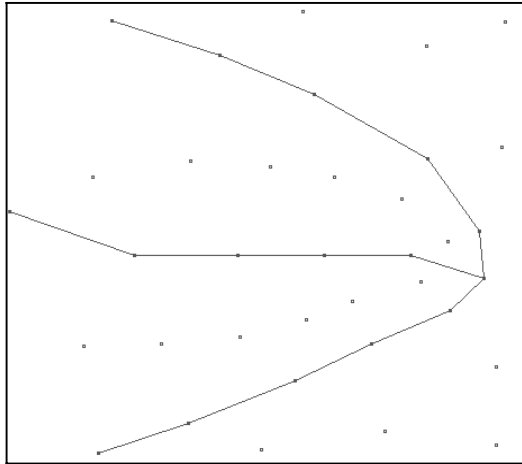


Figure 1: Example of topographical data with constraint lines

4.3.2 DEM construction :

The DEM is considered as an open surface with neither cavity nor pleat. This allows us to use a 2D Delaunay Triangulation method of reconstruction. We use the Bowyer algorithm to compute simultaneously the triangulation and the Dirichlet tessellation :[1],[6].

This triangulation is performed with an iterative algorithm that allows to introduce the points one at a time even for the vertices of the constraints. With this algorithm, we can increase the density of some areas and suppress some points in regions of lower interests or regions that are simplest to describe.

Then we check the presence of the constraints lines in the triangulation ; If some of them are missing, they are forced to appear. If a constraint doesn't appear, it means that is sampling is not adapted to the local sampling. In that case, we increase the density of the constraint in order to have a sampling that take into account the constraint neighbourhood. Then we are sure to make the constraint edge appears as an edge of the graph.

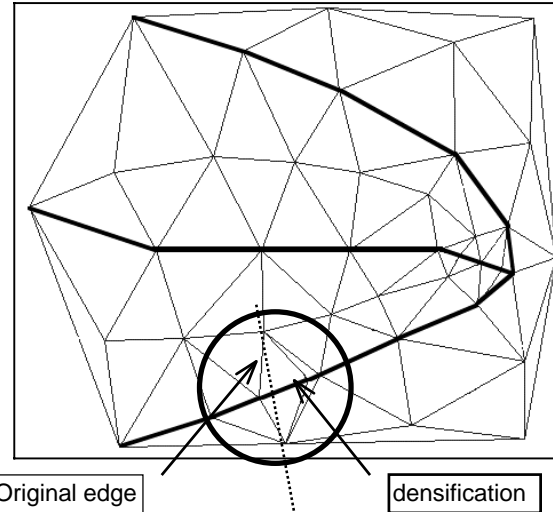


Figure 2:The constraint triangulation of the data. We can see the constraint edges as graph edges.

4.4 Properties:

The properties of this representation can be split into two parts. The properties that allows us to easily design a more accurate DEM, and the properties useful for the use of DEM in simulation

4.4.1 Properties for DEM design :

- Multi-sources : The data can come from various origins : radar images, optical images, map. In order to use them simultaneously all we have to do is to reference them in a unique system of reference (e.g. WGS84)
- Irregularity : The irregular structure of the mesh and the iterative insertion mode allows to handle data at different sampling rate. For instance, this structure can include a TIN mesh and a regular grid mesh.
- Iterative algorithm : this algorithm allows the dynamic update of the DEM, inserting or deleting vertices. This property is also used for multi-scale representation and for moving or zooming (to have a local higher scale) a region of interest.
- Constraints : The use of constraint lines appearing as edges in the DEM mesh warrants a good realism for a low number of necessary points. This helps modelling a wide area at a low cost.

4.4.2 Properties for exploiting DEM in simulation :

- Distortion ability : The DEM construction mode (using 2.5D points) allows to correct one point height without modifying the whole triangulation. Actually, because of its computation mode the mesh can be modified by changing vertex height (for instance because of soil erosion) or including new points because of a shape transformation (for instance a landslide).
- Continuous differentiable DEM : The Delaunay triangulation is the best approximating surface (for minimising the flexion energy) of a set of scattered data [8]. So we can compute a continuous spline based surface model from the mesh of the DEM.
- Region segmenting: the duality between the Delaunay triangulation and the Dirichlet tessellation (nearest

neighbour partition) is preserved by this structure. So we can see the DEM as a planar graph or a spatial segmentation.

- **Multi-scale representation :** the iterative algorithm allows to compute dynamically a mesh with no fixed scale by masking or inserting vertices.
- **Contour line extraction :** Because the slopes are non ambiguous, the computation of the contours lines is easier and more accurate.

4.5 Qualification and validation of our representation :

The development of this structure was driven by the respect of the quality criteria. The triangular facet structure offers a good clinometric accuracy and the morphologic realism is guaranteed by including the terrain structures as DEM constraints.

Finally, the preservation of the Delaunay triangulation induced partition helps the DEM exploitation for simulation and improve the results interpretation.

5. A THEMATIC APPLICATION : THE AVALANCHE PATH ANALYSIS :

We have used this new structure to analyse dynamically the avalanche path. Our aims were:

1. First, from punctual data and a terrain sketching to compute a DEM of avalanche areas using our structure.
 2. Then, to dynamically simulate the avalanche paths and determine the risk areas.
 3. Finally, to test protection devices until risk elimination.
- This leads us to work with the following simulation graph (Figure 3).

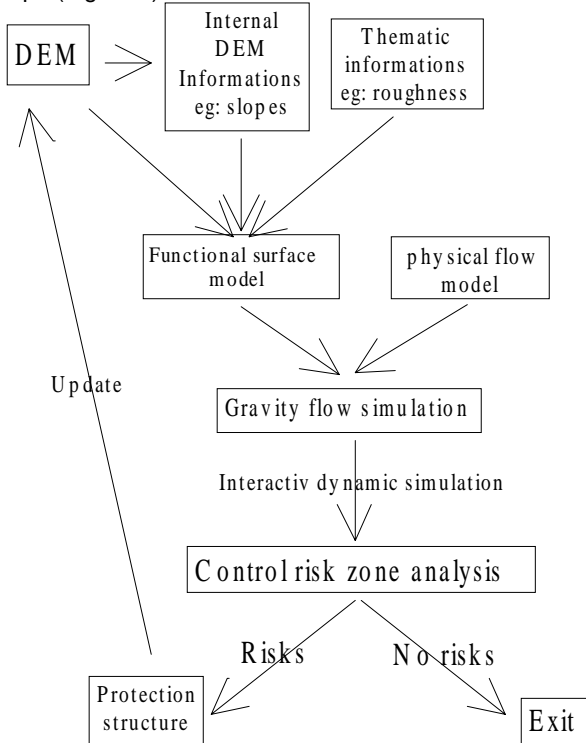


Figure 3: Avalanche simulation model and decision tree.

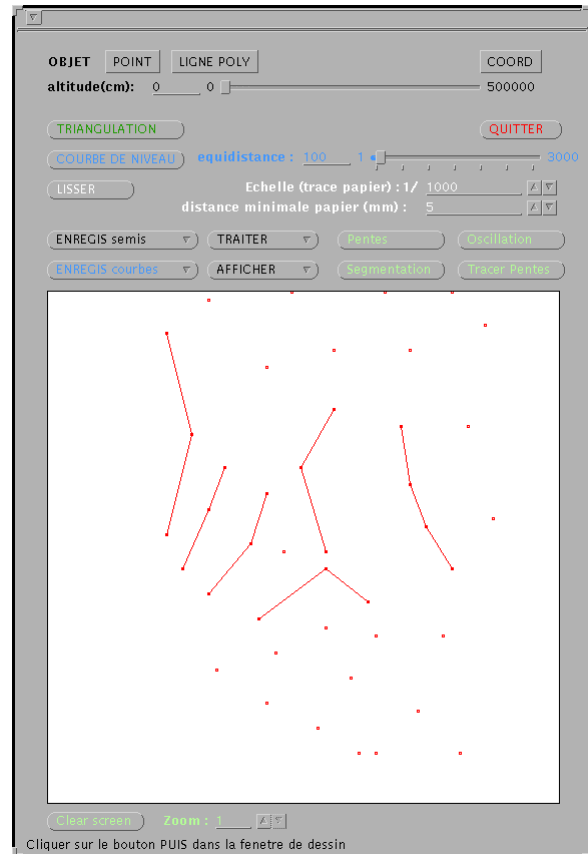


Figure 4: Software interface and topographic data.

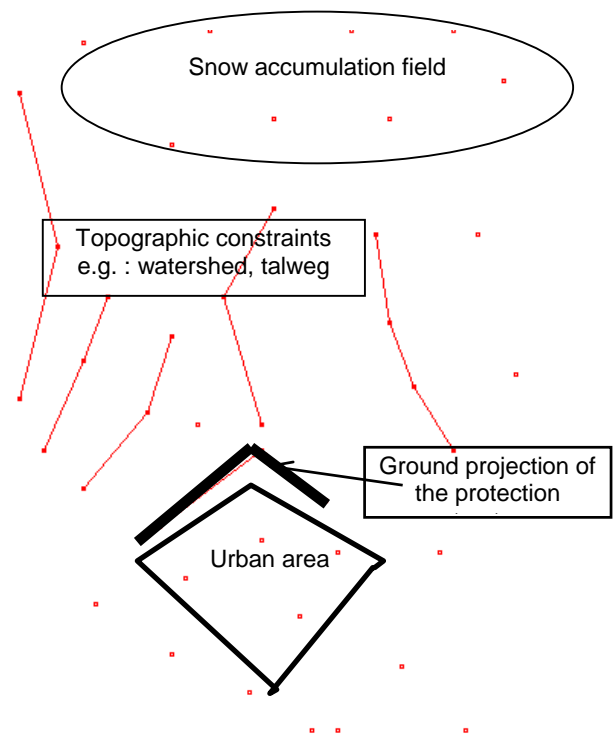


Figure 5: data presentation.

The represented area is a mountainous landscape of 5,5x4 km (i.e. 22 km²) with a height variation of 670m from a lower altitude of 530m.

The constraints correspond either to watershed

or talweg (Figure 5). The shape and location of the protection wall (no elevation) is fixed and is included as a constraint in the DEM. This structure height is computed on the terrain ground. So the contour lines and the avalanche path are not modified by its presence.

We compute the DEM (Figure 6) where we can see the constraints used as triangulation edges. The analysis of the corresponding Dirichlet tessellation shows the urban modelling with four cells (Figure 7). The contour lines at 50 meter give a good idea of the terrain shape (Figure 8).

Finally, we compute the avalanche paths from a start point located by the user. We note (Figure 9) that the urban area is in a risk zone. So, we need to increase the height of protection wall.

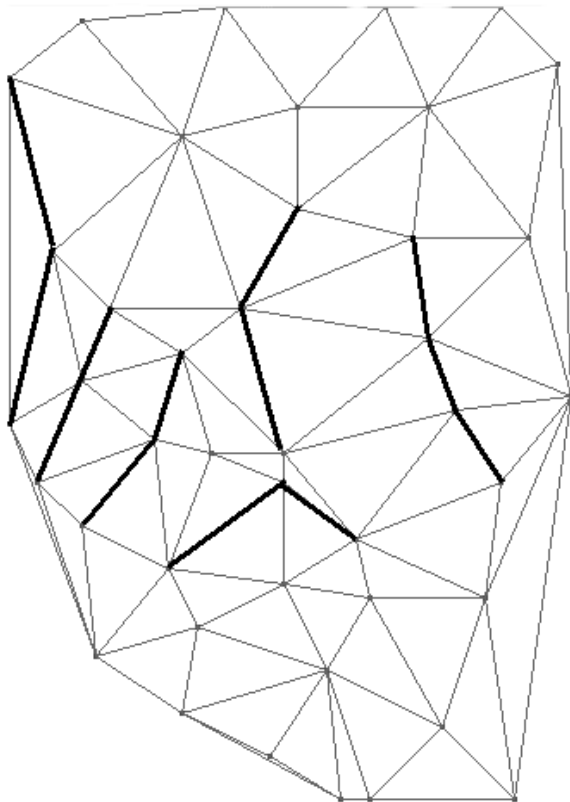


Figure 6: Computed DEM.

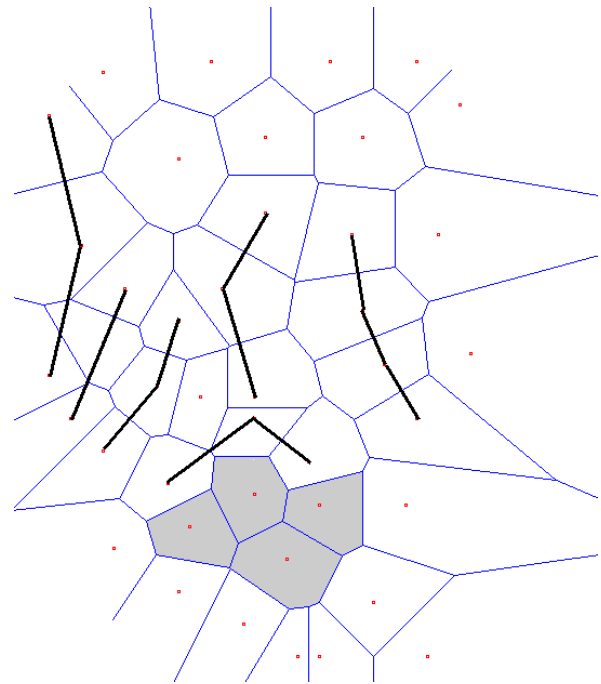


Figure 7: The Dirichlet tessellation associated to the Delaunay constrained triangulation (DCT). 1150m.

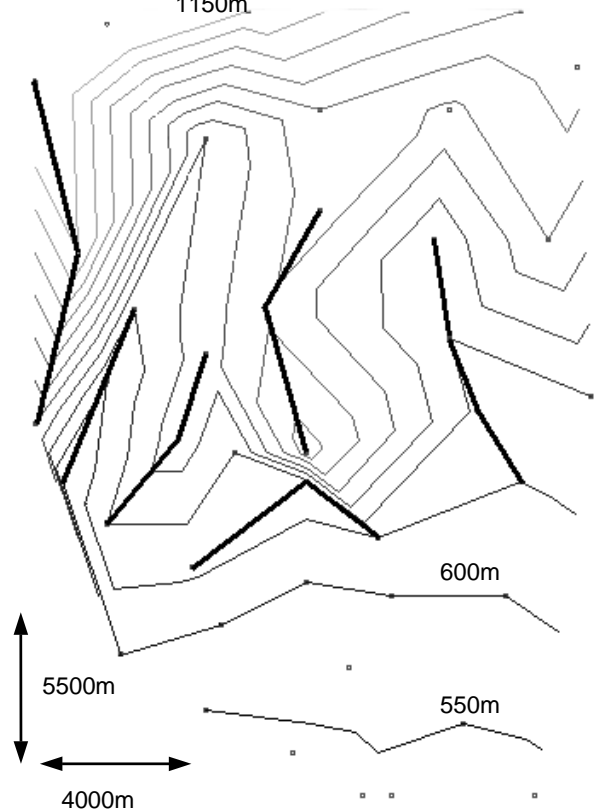


Figure 8: DEM extracted contour lines at 50m.

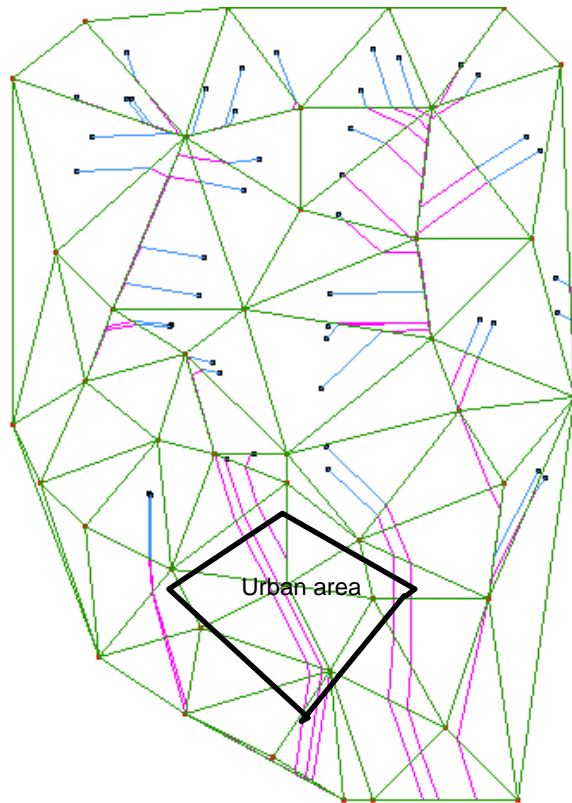


Figure 9 : Avalanche path simulation using the computed DEM.

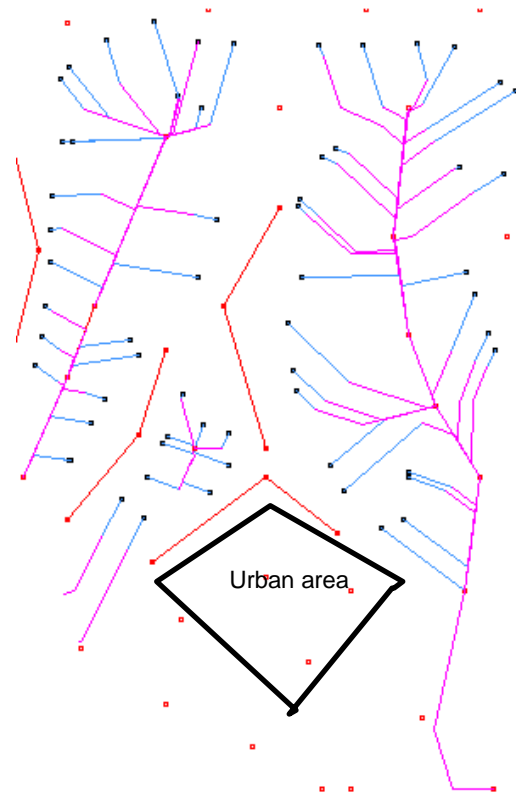


Figure 11: Control simulation of avalanche path : the urban area is protected.

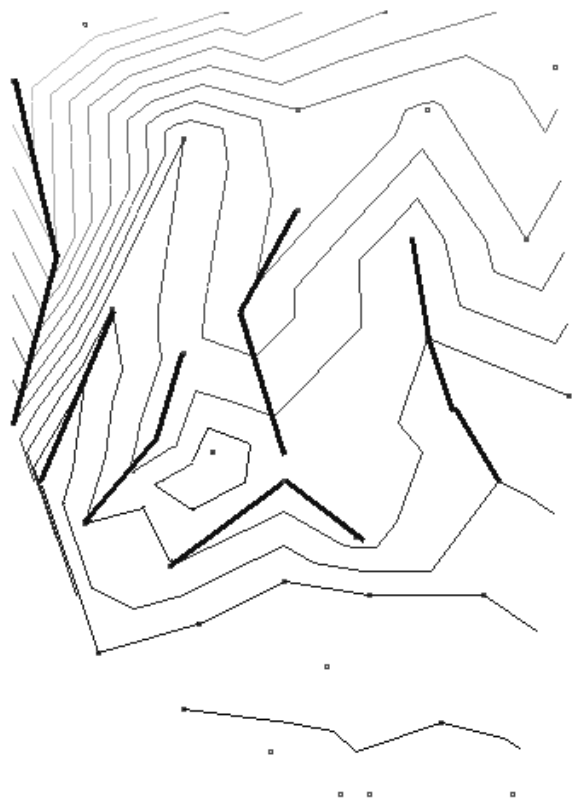


Figure 10: Contour lines at 50m with the protection wall installed.

To protect the urban area, we construct a protection wall whose height is adjusted by successive simulations (the ground location and the shape are fixed). We can see its impact on the contour lines (Figure 10) . Its efficiency is confirmed by the control simulation (Figure 11).

6. CONCLUSION:

We have seen that the standard DEM structures have advantages and drawbacks without being efficient for environmental simulation. The new proposed DEM structure is an evolution of the current representation models driven by a simulation and quality aim.

The first thematic application, using this new structure, offers interesting abilities for simulation.

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