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Intelligent meshing for two dimensional overland flow modelling; a comparison of two methodologies

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INTELLIGENT MESHING FOR TWO DIMENSIONAL OVERLAND FLOW MODELLING; A COMPARISON OF TWO METHODOLOGIES

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Abstract

Two dimensional flow modelling is becoming widely used for urban pluvial flood modelling and is a very effective tool for assessing overland flood flow paths. Given the high resolution LiDAR ground elevation data now widely available, the accuracy of the hydraulic model is dependant largely upon the refinement of the model mesh or grid in representing the ground model topography. This paper considers methods for the accurate representation of overland flow paths in unstructured triangular meshed hydraulic models without the requirement to model the entire system at a high level of detail. The methods involve refinement of the 2D mesh in areas of complex topography and allow less refinement in less complex areas. This approach attempts to maximise the efficiency of the model in terms of representing flow paths while minimising computer run times.

To perform the study presented in this paper two simple intelligent mesh approaches have been selected to be applied in a case study test in conjunction with the 2D hydraulic modelling platform InfoWorks Collection System (IWCS). The numerical results provided by the hydraulic modelling engine have been compared using different mesh resolutions in terms of flood extent and run time. The hydraulic results given by the intelligent mesh methods show an improvement in some cases when compared with their equivalent baseline scenarios. It must be noted that these results presented here are the outcome of limited sensitivity testing and represent an initial phase of research. Further work is ongoing to understand fully the variables which influence the performance of the methods.

1. Introduction

Two dimensional flow models have been increasingly used in flood modelling and are providing a valuable tool in the assessment of flow paths and thereby the receptors of flooding. Light Detection and Ranging (LiDAR) technology has allowed the rapid compilation of detailed ground models usually at 0.5 to 2m horizontal resolution on which hydraulic flow models can be based.

However, 2D flow modelling is considerably more computer intensive than the 1D models historically used, and hence, often results in significantly increased run times. This in turn leads to a trade off between the run time of the 2D model and accuracy of the model at representing the 2D surface. Larger mesh elements allow models to run more quickly but may not correctly represent all the features of the surface. Often the full detail of the underlying topography is not represented in the hydraulic model. Usually 2D flow models comprise either a regular grid or an unstructured triangular mesh to represent the ground surface. Unstructured triangular meshes have the advantage that triangle sizes can vary within a mesh, allowing the user to produce a finer mesh in areas requiring detailed analysis and a coarse mesh overall to achieve manageable run times. The optimal 2D mesh will therefore represent the 2D surface with sufficient accuracy to give confidence in model results while maintaining a manageable run time.

The work detailed in this paper represents a preliminary study to determine the influence that the discretisation of the topography can have on the hydraulic results provided by flood inundation models. An ideal compromise solution to the issue of resolution versus runtime would be an automated meshing algorithm to capture the main features of the terrain, without increasing run time beyond reasonable limits. In this paper two simple intelligent mesh methodologies have been considered and will be described in the Section 2. In order to study the applicability of intelligent meshing in practical situations a test case study has been selected and four baseline meshes with different resolutions have been generated using standard meshing algorithms. The hydraulic results obtained with these standard meshes will be used as a reference to check the improvement derived from the use of the intelligent meshing methodologies.

2. Mesh refinement methodologies

The methodologies developed in this study work on the premise that areas of complex topography will require a more refined mesh to correctly represent flow paths. Topographically complex areas are characterised by rapid changes in slope and includes features such as embankments and cuttings for roadway, railways and drainage in urban environments.

The InfoWorksCS 2D (IWCS) hydraulic model has been used to test these intelligent meshing methodologies. IWCS uses an unstructured triangular mesh and possesses a range of features for mesh editing, import/export from GIS tools and a powerful visualisation engine, which make it ideal for running these meshes in a case study catchment.

2.1 Refinement based on Ground Model Slope (Method 1)

This methodology is based on the generation of mesh zones from the digital terrain model (DTM), depending on the slope of the ground model. These mesh zones are polygon objects that allow the user of IWCS to specify different resolutions throughout the mesh. Therefore, areas with steep slopes will be more refined than flatter areas.

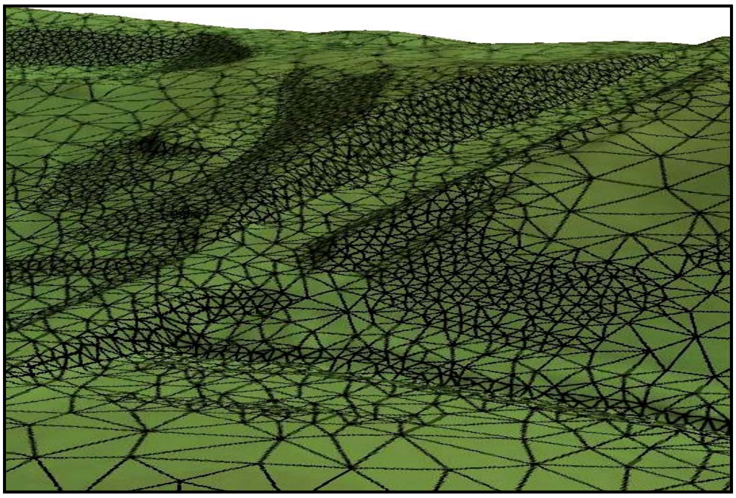

Figure 1: Higher resolution meshing in steeper areas defined in Method 1

The procedure of generating mesh zones is carried out via a GIS pre-processing of the DTM. From the DTM a slope map is calculated and then classified based on a series of slopes. The different slope bands will form areas where mesh polygons will be created. Mesh polygons will be cleaned and smaller polygons removed. The resulting mesh polygons will be imported into IWCS to define zones of higher resolution within the mesh. Figure 1 shows an example of the resulting mesh obtained after carrying out the methodology described above. The steep banks have been defined as mesh zones and have been refined accordingly. The triangles in the remaining area use a coarser mesh.

2.2 Refinement based on Mesh Triangles. Additional vertices method (Method 2)

This methodology is based on the refinement of a base mesh that has already been generated via standard meshing methods as described by Murillo et at [1]. Therefore, the refinement process starts from a discretisation of the DTM given by the vertices of the base mesh. Hence, special care has to be taken in order to select an appropriate resolution for the base mesh, because all the topographical features at smaller scale than that resolution will be not captured.

The parameter that dictates the areas that are going to be refined is the gradient of the slope, according to a tolerance parameter set by the user. The slope of the triangles of the base mesh is given by the plane made up from its three vertices.

To locate the areas to be refined, the slope of each triangle is compared with the slope of its neighbour triangles. The triangle will be refined if the difference in absolute terms between these slopes is greater than the tolerance selected by the user.

The process of refining a particular triangle is based on the division of its original faces, adding new vertices in the mid points as shown in Figure 2. Therefore, four new smaller triangles will substitute the original triangle. An example of this process is shown in Figure 2 a) and the resulting refined mesh in Figure 2 b).

This process of refinement can be repeated again on the resulting mesh, leading to a second refinement and so on. But it does not seem to be advisable to go beyond a second level of refinement, as the aspect ratio of the triangles can be degenerated in excess.

3. Case study application

A UK location has been selected as a case study to test the two intelligent meshing methodologies described in the previous section. LiDAR data with a 1m horizontal resolution was available giving a highly accurate ground model on which to base the hydraulic modelling. The town also possesses a range of topographic features influencing flow paths including embankments, steep sided valleys within the town and cuttings. These features are not unusual in urban drainage situations, hence the findings from the case study are likely to be applicable across wider urban environments.

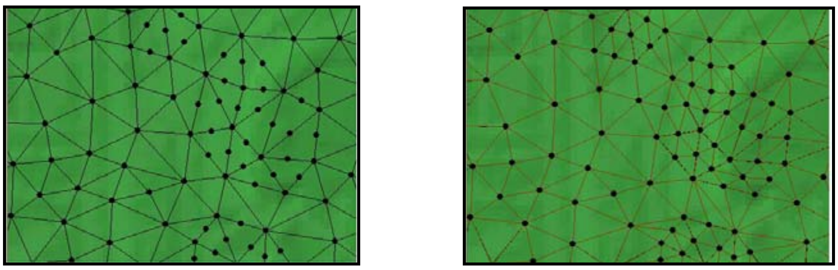

Figure 2 – Refinement based on mesh triangles a) Additional vertices b) Refined mesh

The same mesh outer boundary was used for all the meshes that have been created. Two inflows have been applied to the mesh at the high points local to the channel boundaries in the north of the catchment, each to deliver a constant flow of 5 m^3/s lasting for a period of 5 hours. The mesh covers an area of around 105 ha and a Mannings roughness of 0.02 has been applied throughout the zone. The simulations have been run on a 64 bit Intel Core i7 CRU. The machine is dual quad core with 8 GB RAM.

3.1 Baselines

Four meshes have been created with different resolutions using a standard meshing algorithm, therefore topographical characteristics are not accounted in the meshing process. These four meshes have been generated as baseline cases with resolutions of $2m^2$, 10 m^2, 50 m^2 and $100m^2$, so their results can be compared with those obtained using the intelligent meshing methodologies (Table 1 Appendix).

3.2 Method 1 Setup

Following the methodology described in the previous section, the DTM raster has been converted into a 1m slope raster, and then re-classified in 2 slope bands; a) from 0 to 10 degree slope and b) greater than 10 degree slope. The selection of the limit between slope bands has been made according to the average slope in the area of the case study. All the polygons generated from band b) smaller than $20m^2$ have been deleted to avoid small irregularities of the terrain being included in the mesh. The rest of the polygons have been imported into IWCS to define mesh zones in the model, leaving the rest of the areas with a default mesh size.

Table 2 in the Appendix shows a list of meshes that have been created following this refinement method with their default and refined triangle sizes. The aspect ratio of the triangles has been set to a value which prevents the generation of long and thin triangles.

For simplicity only two slope bands have been used, but this methodology could be extended to be performed with a greater range of slope bands.

3.3 Method 2 Setup

Following Methodology 2 described in the previous section a series of meshes have been generated. Several slope gradient tolerances and levels of refinement have been applied. The base meshes where the refinement method have been applied are the baselines meshes with the following resolutions: $10m^2$, $50m^2$ and $100m^2$. One level of refinement has been performed using the following tolerances, 0.05 and 0.1. Moreover, second refinement has been also carried out using the $50m^2$ and $100m^2$ base meshes with two different tolerances.
The list of meshes that have been generated and tested using this methodology are shown in table 3 in the Appendix.

4. Results

For brevity, only a summary of the results obtained from the study are going to be presented in this section. The result tables with the information about all the cases that have been run are shown in the Appendix. In these tables there is a description of the mesh size used in each one of the cases, a statistical compilation of the results compared against the $2m^2$ baseline and the run time.

The results of the baseline cases are shown below in Figure 3. The results show a large variation in the flow paths depending on the mesh resolution. Figure 3 a) shows the greatest similarity to the $2m^2$ results although there are two distinctive flow paths highlighted which have not been exploited by the 10 m^2 mesh. The results for the 50 m^2 mesh show a greater difference in the flood pathways. There are six noticeable areas where the 50 m^2 mesh has not picked up a major flow pathway. The results from the 100 m^2 comparison show a marked difference with a large area to the east of the catchment not defined as a pathway. This is a clear example of how mesh resolution can affect the hydraulic results obtained from a numerical model. Examining the results in table 1 in the appendix it is clear that the refinement of the mesh improves the accuracy of the results but with a dramatic increase in run time.

A comparison between the results obtained using the refinement methods presented in this paper is shown in Figures 4 and 5. The cases have been selected according to their equivalence in terms of default mesh size and refined mesh size.

In the first comparison the mesh generated by Method 1 has a default resolution of $100m^2$ and $25m^2$ in the mesh zones. The mesh selected from Method 2 is a $100m^2$ mesh with one level of refinement and a slope gradient tolerance of 0.05. As the triangles in the refined areas are substituted by 4 smaller triangles, this is equivalent to having $25m^2$ triangles.

In the second comparison the mesh generated by Method 1 has a default resolution of $50m^2$ and $2m^2$ in the mesh zones. The mesh selected from Method 2 is a $50m^2$ mesh with two levels of refinement, a slope gradient tolerance of 0.1 in the first level and 0.2 in the second. Therefore the original $50m^2$ mesh will have areas refined at approximately 12 m^2 and other areas further refined at approximately $3m^2$.

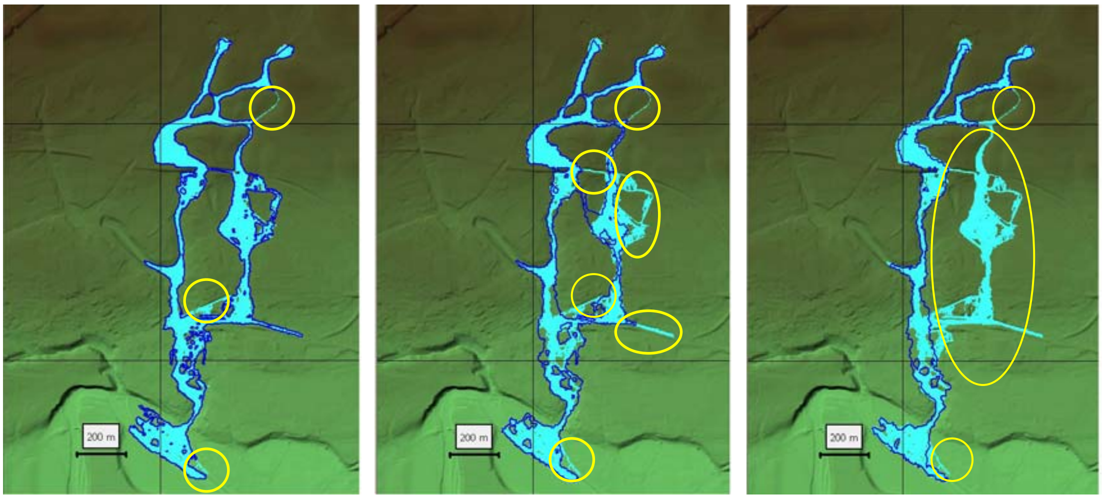

Figure 3 - Baseline results comparison a) $2m^2$ (shaded area) and 10 m^2 (dark boundary) b) $2m^2$ and 50 m^2 c) $2m^2$ and 100 m^2

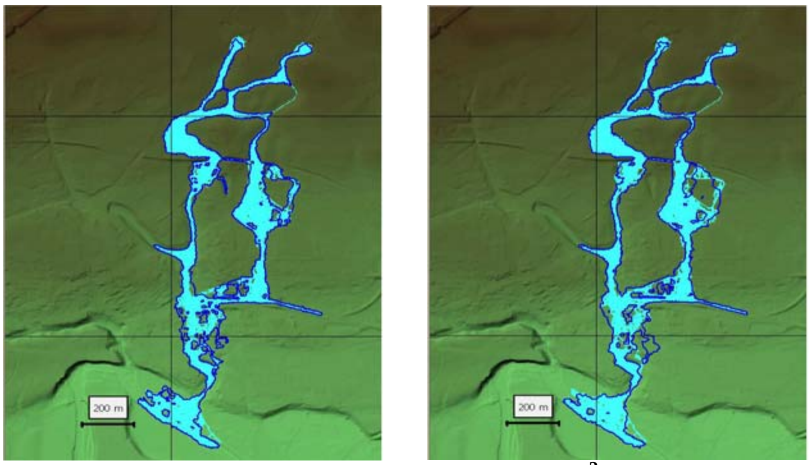

Figure 4 - Comparison between results from the baseline $2m^2$ case and a) Method 2, 100 m^2 mesh, 1 level of refinement and a slope gradient tolerance of 0.05 b) Method 1, 100 m^2 mesh with refinement of 25 m^2 in the slope bands.

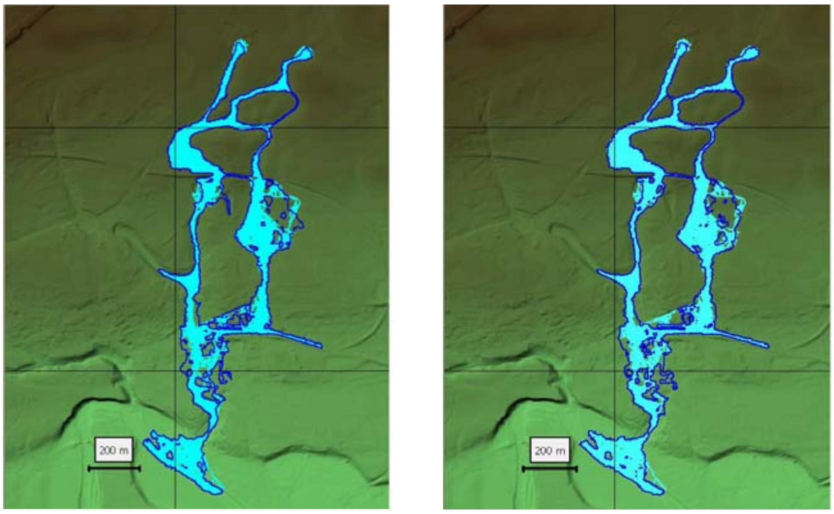

Figure 5 - Comparison between $2m^2$ baseline results and a) Method 2 mesh refinement, $50m^2$ mesh with 2 refinements. First with a slope gradient tolerance of 0.1 and second with 0.2 b) Method 1 ground model refinement, 50 m^2 mesh with a refinement of 2 m^2

The differences between refinement methods in terms of flooded areas, for the equivalent cases, are not significant. There is however a clear improvement in the results when the two meshing methods are compared with those obtained from the baseline cases. In the first comparison the agreement with the baseline $2m^2$ case has increased from 54% for baseline $100m^2$ (Figure 3c), to 89% using Method 1 and 85% using Method 2 (Figures 4 a and b). The run time of method 1 is much higher than the $10m^2$ baseline mesh which offers a higher level of accuracy hence this method performs poorly on this criterion. The method 2 runtime is very much lower and offers a good combination of run time versus accuracy. In the second comparison, the agreement with the baseline $2m^2$ case has increased from 79% for baseline 50m2 (Figure 3b), to 91% using both Method 1 and 2 (Figures 5 a and b). The run time of both methods is higher than the $10m^2$ baseline run which offers higher levels of accuracy hence both methods perform poorly on this criterion.

The results in the appendix clearly show that for similar levels of accuracy, Method 2 is around one order of magnitude faster in run time. This is because the number of triangles in the meshes generated by Method 1 is larger than the equivalent cases using Method 2. The number of new triangles generated by Method 2 is controlled by the Method itself. The number of new triangles generated by Method 1 depends on the definition of the mesh zones. In order to adapt the mesh to the shape of the mesh zones, the meshing algorithm generates small triangles which have the effect of decreasing the time step of the hydraulic model, leading to an increased run time.

It is important to note the implications intelligent meshing can have on the overall performance of the model. Model run time is in general dictated by two factors, the number of wet cells and the size of these wet cells. The larger the number of wet cells and the smaller the size of these cells, the longer the run time. In particular, when using Method 2, the intelligent mesh algorithm refines the mesh in areas with sudden changes of slope, which normally represent natural water courses. Moreover, it is important to bear in mind that the time step of the hydraulic model is a global variable that is calculated in wet cells and is proportional to the square root of the area of the cells. The combination of both factors, larger number and smaller wet cells, might lead to longer run times using intelligent meshing compared to uniform meshes, even if the number of total cells is smaller.

5. Conclusions and potential improvements

Figure 6 in the appendix gives an overview of the performance of the intelligent meshing methods in terms of accuracy against a very refined mesh and run time. The figure shows that Method 1 (standard mesh) performs poorly with higher run times and lower accuracies than baseline meshes. Method 2 shows potential for an increase in efficiency with four scenarios falling below the baseline curve.

Method 1 is likely to perform poorly for two reasons: Firstly, the mesh is refined based on ground slope rather than change in ground slope as in method 2. This means that areas of uniform steep slope will be meshed which may not affect flow paths. The selection of slope classes as a refinement parameter will also vary depending on the overall steepness of the catchment whereas the change in slope is a more independent parameter. Secondly, the production of mesh zones in steep areas may produce polygons with complex outlines forcing many unnecessarily small triangles to be formed around the zone margins. A first attempt to aggregate those unnecessary small triangles generating a so called “virtual mesh” has given a considerable reduction in running times (see Table 2 and Figure 6). This indicates that Method 1 can still be efficient if the polygons generated are simplified.

It appears that within method 2 the most effective scenarios used meshes with one level of refinement based on $100m^2$ and $50m^2$ base meshes. This implies that two levels of refinement increase run time without improving accuracy and that fine base meshes already capture sufficient detail to make further refinement unnecessary.

Much further research is required into this topic in order to fully understand the sensitivity of the parameters used for the intelligent meshing (e.g. slope bands in method 1) and explore the potential of alternative approaches such as applying method 1 using change in slope rather than slope as the refinement parameter or simplifying mesh zones outlines to reduce the number of small triangles. An understanding of the effect on hydraulic model results of random vertex placement in unstructured mesh generation would also be useful by running numerous meshes with the same resolution but differing triangle orientation. The use of a range of ground models would also be beneficial in understanding performance under a range of different topographies.

Neither method is currently ideal in the sense that method 1 requires meshing of complex polygons and method 2 cannot resolve topography at a finer resolution than the base mesh which is being refined. However, in interpreting Figure 6 is it important to note the following points which indicate the further potential of intelligent meshing methodologies:

1) Intelligent meshing methods are very effective identifying flow paths dictated by relatively small topographic features (e.g. ditches or mounds), especially when you compare results with regular meshes which with equivalent mean triangle size. In this particular study, the steep topography in the DTM meant that the flow paths were relatively insensitive to changes in mesh size. On flatter DTMs and those where flow paths are divergent the capture of small flow paths by intelligent meshing will be most noticeable.

2) Although it has not been quantified yet in this phase of the study, an intelligent meshing approach will generally give more accurate model results (depths and velocities) than its equivalent-size regular meshes

on those areas in which the mesh has been refined. This fact is not actually shown in Figure 6

3) The results shown in this study are a first attempt to use these methodologies. Some of the parameters and procedures still have room for improvement, as it is shown in Method 1 with the aggregation of small triangles.

The potential of both methods has been demonstrated for a number of scenarios and further work may be able to increase the efficiency of the methods and overcome some of their shortcomings. The requirement for more efficient and accurate 2D meshes makes this an exciting area for future development.

6. References

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Appendix

Table 1. Baseline cases

	% Agreement with base line 2m^2	% added areas	% missing areas	Number of cells	Number of active cells	Simulation time (s)
2m^2	-	-	-	811969	162889	22007
10m^2	93	9	7	162920	33535	1612
50m^2	79	16	21	32648	6259	119
100m^2	54	11	46	16236	2168	38

Table 2. Method 1 (* = used in comparison 1, # = used in comparison 2). Results using standard mesh (S) and virtual mesh (V). NA = not available.

	Max triangle size (m^2)	Mesh zone triangle size (m^2)	% Agreement with base line 2m^2	% added areas	% missing areas	Number of cells	Number of active cells	Simulation time (s)
S	100	50m^2	89	20	11	51196	11940	3927
S	*100	25m^2	89	19	11	52480	12333	4112
S	100	2m^2	90	18	10	156031	33878	11991
S	50	25m^2	92	17	8	62383	14270	4261
S	50	12m^2	91	18	9	67174	15359	4910
S	#50	2 m^2	91	17	9	164638	35632	12424
V	100	50m^2	88	22	12	22823	NA	924
V	100	25m^2	88	21	12	27135	NA	1092
V	100	2m^2	94	33	6	108172	NA	4760
V	50	25m^2	93	22	7	42559	NA	1423
V	50	12m^2	91	21	9	50120	NA	1617
V	50	2 m^2	92	23	8	125413	NA	5067

Table 3. Method 2. (* = used in comparison 1, # = used in comparison 2)

Max Triangle size (m^2)	Number of refinements	Maximum change in slope	% Agreement with base line 2m^2	% added areas	% missing areas	Number of cells	Number of active cells	Simulation time (s)
10	1	5	95	7	5	427357	89076	8149
10	1	10	96	8	4	294062	61047	5789
50	1	5	91	13	9	84354	18429	754
50	1	10	91	18	9	60377	13459	564
50	2	10	91	17	9	145361	32901	2791
#50	2	20	91	19	9	107175	24932	1964
*100	1	5	85	14	15	43182	9405	236
100	1	10	84	18	16	29758	6890	165
100	2	10	90	20	10	71024	17580	933
100	2	20	85	18	15	52602	12949	650

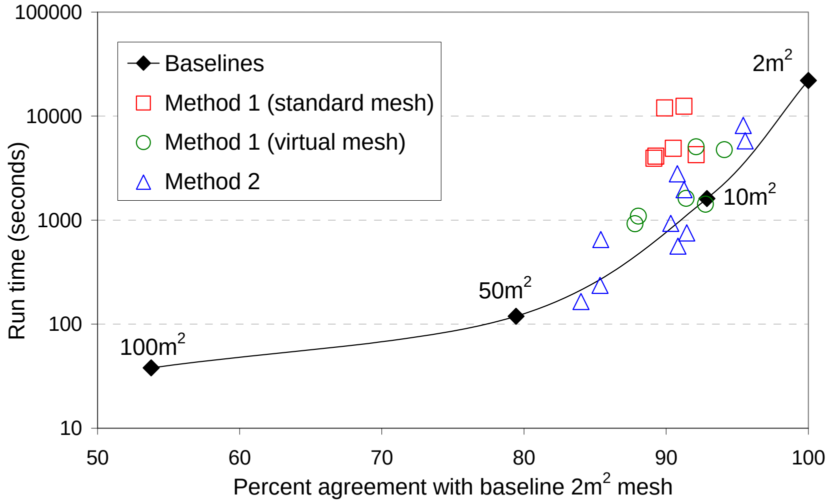

Figure 6 Comparison of run time with percent agreement for the baseline and intelligent meshes

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