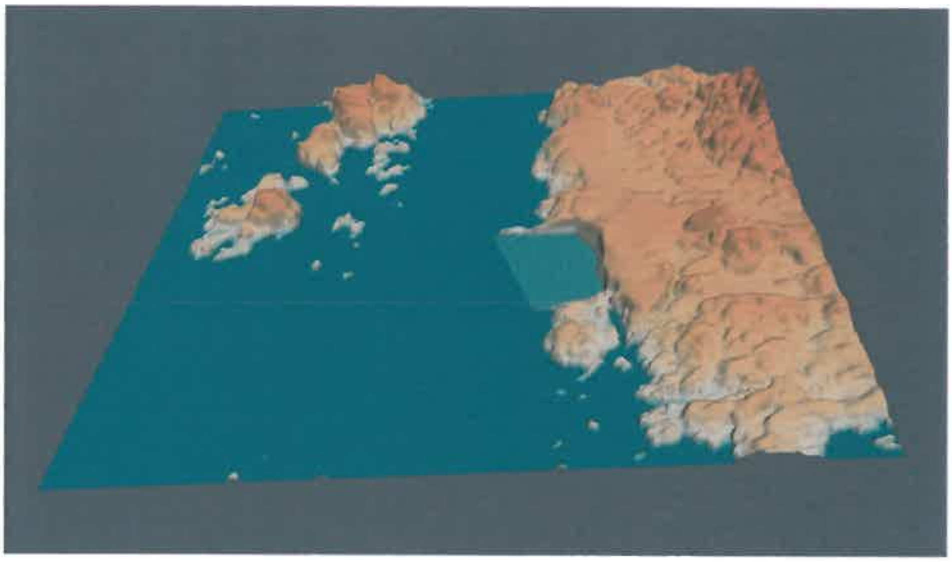
SINTEF A25598 - Unrestricted

Report

Impact Assessment of Adverse Turbulence due to Landscape Changes close to Airports

Mathematical and Software Tools for Terrain Modification and Impact Assessment

Author(s)
Karstein Sørli
Adil Rasheed



Example of excavating an area close to Bergen Airport Flesland.

SINTEF ICT
Applied Mathematics
20th December 2013

SINTEF IKT
SINTEF ICT

Address:
P. O. box 4760 Sluppen
NO-7465 Trondheim
NORWAY

Telephone: +47 73593000
Telefax: +47 73592971

postmottak.IKT@sintef.no
www.sintef.no
Enterprise / VAT No.:
NO 948 007 029 MVA

KEYWORDS:
terrain
modifications
atmospheric turbulence
aviation impact

Report

Impact Assessment of Adverse Turbulence due to Landscape Changes close to Airports

Mathematical and Software Tools for Terrain Modification and Impact Assessment

VERSION
1.0

DATE
3rd December 2013

AUTHOR(S)
Karstein Sørli
Adil Rasheed

CLIENT(S)
Avinor AS

CLIENT'S REFERENCE
Erling Bergersen

PROJECT
102002213

NUMBER OF PAGES AND ATTACHMENTS
14 0

ABSTRACT
In places dominated by irregular terrain, significant topographical modifications are often required to develop new or improve the existing infrastructure like roads, buildings, airport terminals and harbours. If the modifications are proposed close to an airport then it directly impacts flight safety. Impact assessment then attains significance. Here, we describe a numerical algorithm for the excavation of an arbitrary polygonal domain within an area with a given topographic description. The potential of the algorithm and its numerical implementation is demonstrated by applying it to an artificial wavy terrain and then to a couple of Norwegian airports. The potential of assessing modified flying conditions close to the ground is also presented.

Although the present study is mainly focused on *terrain-induced atmospheric turbulence* close to airports, the outcome of the present work can also be utilized for other purposes, like *building-induced turbulence* simulations.

PREPARED BY
Karstein Sørli

SIGNATURE
Karstein Sørli

CHECKED BY
Runar Holdahl

SIGNATURE
Runar Holdahl

APPROVED BY
Trond Runar Hagen

SIGNATURE
Trond Hagen

REPORT NUMBER
SINTEF A25598

ISBN
978-82-14-05335-7

CLASSIFICATION
Unrestricted

CLASSIFICATION THIS PAGE
Unrestricted

Contents

SINTEF

1 Background

Severe air turbulence in the vicinity of the runway threshold at an airport may endanger landing or departing aircraft. Such turbulence can be caused by buildings or complex terrain close to the airport. The problem is increasing due to terrain modifications required by changes and improvements of existing and new infrastructure like roads, buildings, airport terminals and harbours.

Airports Council International (ACI)[10] recommends that, in cooperation with the air navigation service provider and civil aviation authority, numerical simulations and/or wind tunnel testing are performed on models of proposed new buildings and changes of landscaping which may affect the safety of aircraft during approach and departure. ACI also recommends that suitable regulations be developed and incorporated in *ICAO Annex 14*[11] and the *ICAO Airport Services Manual*[9].

The ICAO Manual on *Low Level Wind Shear* notes "it will always be a serious hazard for aviation". As proximity is a critical factor, wind shear and turbulence issues will usually be an on-airport consideration. The potential impacts of proposed developments close to runways should be appropriately modelled.

Schiphol Airport in the Netherlands takes a proactive approach to assessment of the potential risks posed by new buildings encroaching on the aerodrome, undertaking modelling for all new buildings. They use a *one in 35 ratio rule of thumb* (see [3]) for investigating buildings over a certain height to distance from any runway centerline. In addition, a range of factors need to be considered: the bulk and form of the building, both upstream and downstream wind flows, prevailing and adverse seasonal weather conditions, the potential to mitigate impacts upstream through landscaping or other development activity and the specific location and orientation of the development activity in relation to critical points on the runway.

Even at smaller airports, encroaching development and vegetation off-airport but close to the runway may significantly increase the potential for adverse flying conditions, particularly for landing light aircraft. Increased planning powers for state, territory and local government decision-making may be required to prevent encroachment on aerodromes where existing or potential safety impacts are identified.

There are a large number of variables in determining the impact of turbulence from a development: shielding and actual building profile are major considerations as are the potentially mitigating factors up and downstream of terrain, vegetation and development. This may require coordination of on and off airport development activity at some locations.

It might not be possible to set a practicable standard and provide specific guidance and regulations for mechanical turbulence. It might be more appropriate to require expert modelling and risk assessment on a case-by-case basis. Seeking a credible assessment for off-airport developments might be an acceptable approach. Should there be a consistent industry standard for mechanical turbulence and wind shear? If so, should the standard be proscriptive or allow for a case by case assessment? Should expert modeling work on turbulence and wind shear be mandatory for developments in close proximity to runways and who should bear the cost? These are questions that have been raised. We do not try to answer all these questions, but we assume (as others), that a case-by-case study is needed due to the diversity of infrastructure improvements near by airports that may be planned.

2 Introduction

In the present work, building-induced turbulence is not considered since it requires slightly different tools than the ones we are dealing with in this work. Here, terrain-induced turbulence and wind shear are the main focus. This article describes a computational procedure and software tool for the excavation of *an arbitrary polygonal domain* within an area with given topographic description. This includes both a basal theoretical description of the excavation procedure as well as some examples of usage.

The *terrain editing tool* developed makes it possible to excavate arbitrary convex polygonal areas from an existing terrain, for subsequent turbulence calculations by a CFD code like SIMRA [2] (**S**emi-**Im**plicit **RA**NS-**A**veraged), illuminating the consequences of planned terrain modifications, with respect to flying conditions during take-off and landings. Examples of such consequence analyses are given in Rasheed and Sørli [4] and [5]).

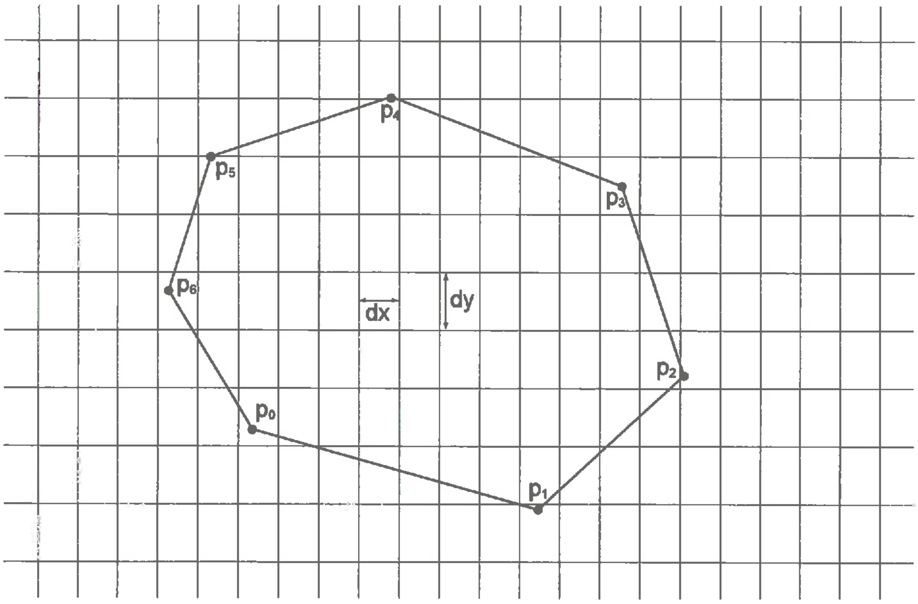


Figure 1: Polygonal domain inside a homogeneous height map grid.

However, the tool developed makes it easy to modify the terrain and perform a CFD analysis of the consequences of the terrain modifications.

In addition to the specification of a polygonal area, also the side plane slopes at the edges of the given polygon can be specified. The polygon vertices are given by their actual UTM latitude and longitude coordinates (Universal Transverse Mercator coordinates). Testing on real terrains have been performed on UTM data with a horizontal resolution of $(10 \times 10)\, m^2$.

The SIMRA code mentioned above is also used for resolving the finest turbulence (micro) scales in a nested system with meteorological NWP (numerical weather prediction) codes. It makes use of mesoscale meteorological data and produces a detailed wind and turbulence prediction around the airports. The system as such neither needs any special equipment in the airplane nor at the airport. This system has been approved by the NCAA (The Norwegian Civil Aviation Authority) and has been fully operational since 1st July 2009. For further details it is referred to [6].

3 Method

It is assumed that the terrain topography is described by a homogeneous and structured height map

$$(x_i, y_j, z_{i,j}),\ 0 \leq i < ni,\ 0 \leq j < nj$$

where

$$x_i = x_0 + i\,dx,\ 0 < i < ni \quad \text{and} \quad y_j = y_0 + j\,dy,\ 0 < j < nj.$$

Let a polygonal subdomain of the terrain map be given by the vertices $\mathbf{p}_k$, $0 \leq k < n$ (illustrated in Figure 1 for $n = 7$), and their coordinates be described by

$$((p_x)_k, (p_y)_k),\ 0 \leq k < n.$$

3.1 Interior point to polygon

Given a polygon which lies in a plane, and a single point in the same plane, we would like to have an algorithm for determining whether the point lies inside the polygon. The following algorithm only applies to convex polygons;

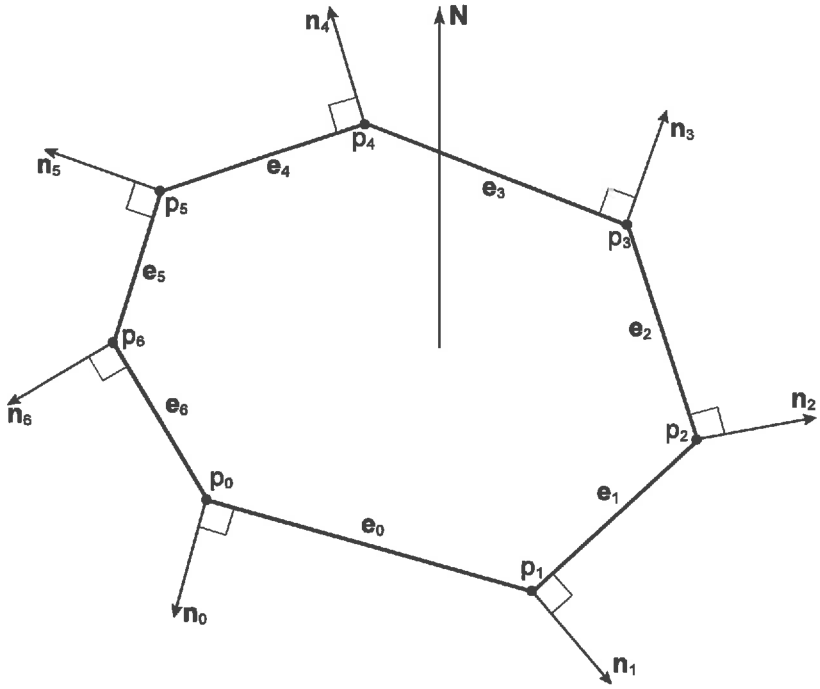


Figure 2: Normals to the polygonal domain and its edges.

those with the property that given any two points inside the polygon, the entire line segment connecting those two points must lie inside the polygon. Such polygons are the intersection of half-planes, which means that if you extend the boundary edges into infinite lines the polygon will always lie completely on one side of each edge line. If a point is on the same side of each edge as the polygon, then it must lie inside the polygon. Different algorithms for *point in polygon* decision is described in O'Rourke [1].

For this algorithm we assume that the vertices of the polygon are numbered $\mathbf{p}_0, \mathbf{p}_1, \mathbf{p}_2, \ldots$ in counterclockwise order. Edge $\mathbf{e}_k$ extends from $\mathbf{p}_k$ to $\mathbf{p}_{k+1}$. Vector $\mathbf{N}$ is normal to the plane containing the polygon. This is easy to construct as $\mathbf{e}_0 \times \mathbf{e}_1$, or as $\mathbf{e}_k \times \mathbf{e}_{k+1}$ for any k. Vector $\mathbf{n}_k$ is an outward-pointing normal for edge $\mathbf{e}_k$. We can construct this as $\mathbf{e}_k \times \mathbf{N}$. Figure 2 illustrates all of these items.

Note that $\mathbf{e}_k = \mathbf{p}_{k+1} - \mathbf{p}_k$, and $\mathbf{n}_k$ is normal to $\mathbf{e}_k$, so $\mathbf{n}_k \cdot (\mathbf{p}_{k+1} - \mathbf{p}_k) = 0$. This means that $\mathbf{n}_k \cdot \mathbf{p}_{k+1} = \mathbf{n}_k \cdot \mathbf{p}_k$. It is easy to extend this to show that $\mathbf{n}_k \cdot \mathbf{p}_k = \mathbf{n}_k \cdot \mathbf{p}$ for any point $\mathbf{p}$ on the line defined by edge $\mathbf{e_k}$. This lets us split the plane into two regions: points $\mathbf{p}$ for which $\mathbf{n}_k \cdot \mathbf{p} \leq \mathbf{n}_k \cdot \mathbf{p}_k$ and points $\mathbf{p}$ for which $\mathbf{n}_k \cdot \mathbf{p} \geq \mathbf{n}_k \cdot \mathbf{p}_k$. Which side is the polygon on? Consider point $\mathbf{p}_k + \mathbf{n}_k$, which is outside the polygon because $\mathbf{n}_k$ is an outward-pointing normal. We have

$$\mathbf{n}_k \cdot (\mathbf{p}_k + \mathbf{n}_k) = \mathbf{n}_k \cdot \mathbf{p}_k + \mathbf{n}_k \cdot \mathbf{n}_k = \mathbf{n}_k \cdot \mathbf{p}_k + |\mathbf{n}_k|^2 > \mathbf{n}_k \cdot \mathbf{p}_k.$$

Thus the half-plane containing points $\mathbf{p}$ where $\mathbf{n}_k \cdot \mathbf{p} \geq \mathbf{n}_k \cdot \mathbf{p}_k$ is on the side of the edge pointed to by the outward-pointing normal; it does not contain the polygon. The half-plane defined by $\mathbf{n}_k \cdot \mathbf{p} \leq \mathbf{n}_k \cdot \mathbf{p}_k$ does contain the polygon.

Our algorithm for determining if point p is inside the polygon is thus:

> $\mathbf{p}$ is inside the polygon if $\mathbf{n}_k \cdot \mathbf{p} \leq \mathbf{n}_k \cdot \mathbf{p}_k$ for each edge $\mathbf{e}_k$, where $\mathbf{n}_k$ is the outward-pointing normal to edge $\mathbf{e}_k$.

3.2 Inclined planes at polygon sides

Since the excavation of polygonal sub-domains in terrain maps is to be followed by "carving out" inclined side-planes at given angles to the horizontal plane, we need to determine the intersection between the terrain and

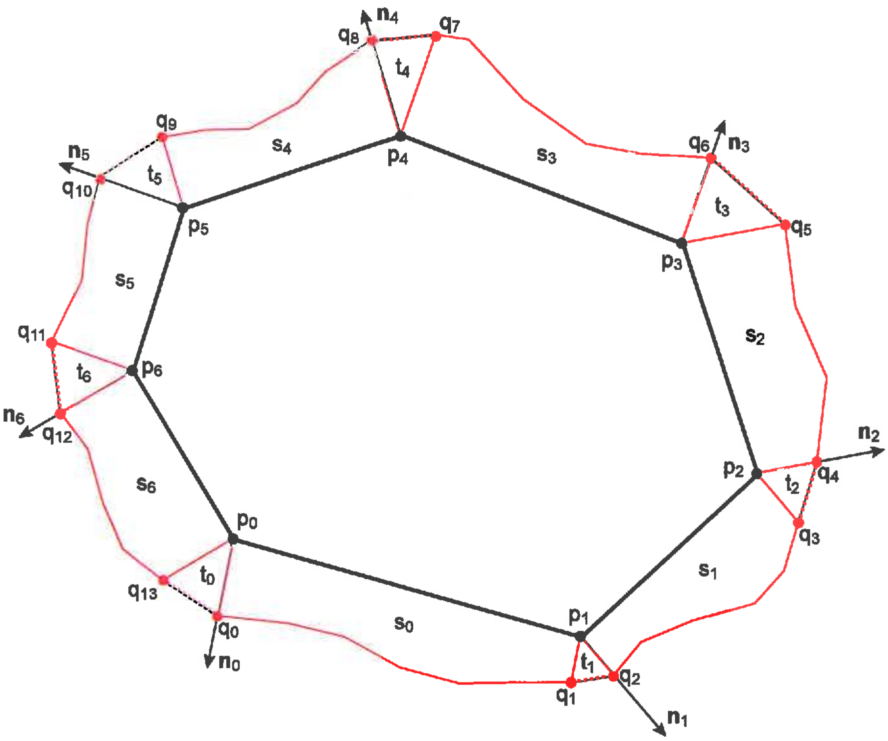


Figure 3: Inclined side-planes at of the edges of the polygon.

these inclined planes for each edge of the polygon. This represent an outer polygon as illustrated in Figure 3.

As noted in the previous section the outward-pointing normal $\mathbf{n}_k$ to each side $\mathbf{e}_k$ of the polygon is given by $\mathbf{e}_k \times \mathbf{N}$. Since $\mathbf{N} = (0, 0, 1)$ in our case we have

$$\begin{aligned} \mathbf{n}_k &= \begin{vmatrix} i & j & k \\ (p_x)_{k+1} - (p_x)_k & (p_y)_{k+1} - (p_y)_k & 0 \\ 0 & 0 & 1 \end{vmatrix} \\ &= ((p_y)_{k+1} - (p_y)_k, -(p_x)_{k+1} + (p_x)_k, 0) \end{aligned}$$

This defines initial estimates of the x and y coordinates of the q-points as illustrated in Figure 3. These coordinates are then translated along the normal vector $\mathbf{n}_k$ far enough to ensure that the inclined plane at this vertex $\tilde{p}_3$ is crossing above the terrain (see Figure 4). This is obtained by using the maximum height z_{max} of the terrain in the actual region. Thereafter the actual terrain crossing point p_3 is obtained by stepping back on the line between p_1 and $\tilde{p}_3$ until crossing is detected. Having the three points p_1, p_2 and p_3 determined (as well as p_4), the coefficients c_0, c_1 and c_2 describing the side plane

$$z = c_0 + c_1 x + c_2 y \tag{1}$$

can be determined. Actually, the farthermost point from the base line is chosen, so in some cases, p_4 is used instead of p_3. This is done in order to make the solver for determining the coefficients c_0, c_1 and c_2 of Equation 1 as robust as possible. The corner planes are determined in a similar manner.

4 Examples

In this section are given some examples of both artificial and real terrains that are changed or excavated in a certain manner.

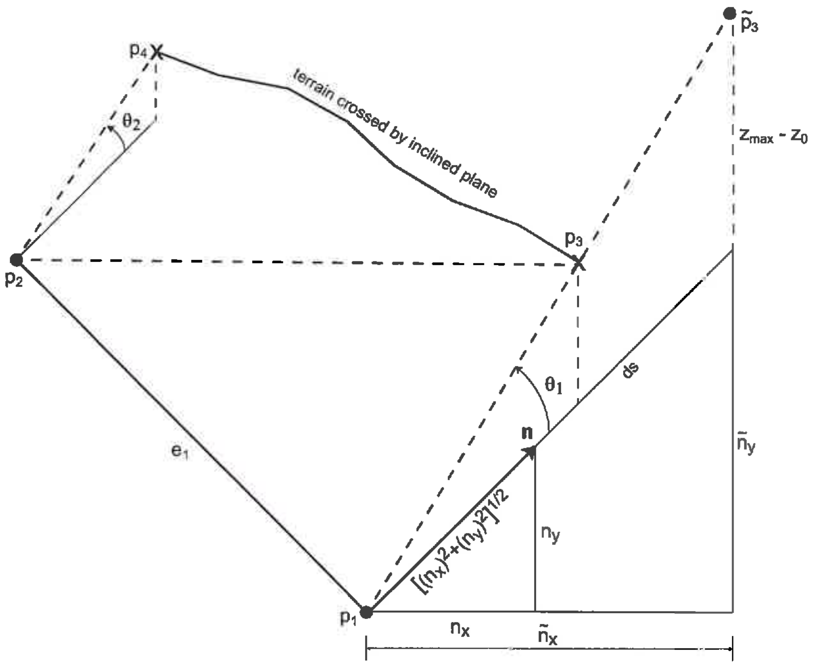


Figure 4: Crossing of inclined side-plane at an edge of the polygon. For clarity: the stippled lines are generally in 3D space, while the other lines are in the horizontal $z = z_0$ plane.

4.1 Excavating Artificial Terrains

The artificial terrains chosen are described by a sinusoidal function

$$z(x, y) = z_{max} \left[1 + \sin(\frac{n_x \pi x}{x_{max}}) \sin(\frac{n_y \pi y}{y_{max}}) \right] ; \tag{2}$$

where n_x and n_y are given frequencies of the *wavy terrain*. These are chosen in order to test the accuracy and robustness of the computational algorithms.

First "a single hill" is partly excavated in the center as illustrated in Figure 5.
Then a multiple sinusoidal terrain is examined as illustrated in Figures 6 and 7.

4.2 Excavating Real Terrains

An example from the Flesland Airport in Bergen, where a harbour is planned, is considered. Table 1 shows the input file for the polygon area that is illustrated in Figure 9. In this case a digital elevation model (DEM) of the actual region is having a horizontal resolution of $(10 \times 10)\ m^2$. Zone 32 of the Norwegian terrain map is illustrated in Figure 8(a) with all its tiles. The actual tile is "outdrawn" in part (b), and a subdomain of this DEM file utilized is illustrated in part (c) of Figure 8.

Simulation of stratified airflow from the west is done and the resulting airflow and terrain-induced turbulence are shown in the Figures 11 and 12. Note that the simulations are done for a somewhat different terrain modification. A complete analysis of the consequences by a specific terrain modification for close to ground turbulence, needs several more simulations with different atmospheric conditions. It may be also required to study different terrain modifications in order to alleviate consequences.

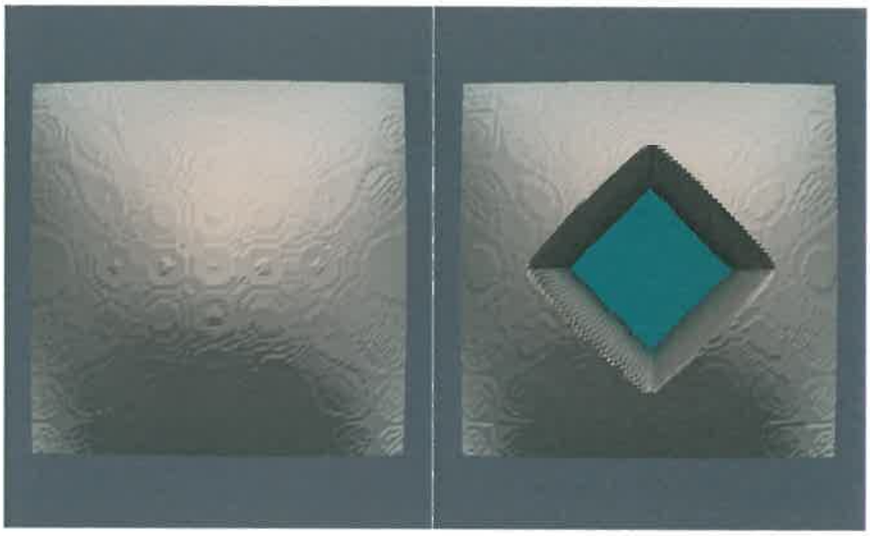


Figure 5: Excavation of a sinusoidal terrain with frequency 1 in both directions. Slopes of sidewalls are 45 degrees.

Table 1: Input file to the terrain editing software tool for the Flesland case.

8	3			*%no polygon vertices, elevation*
290380	6688200	45	45	*%UTM lon, lat, slopes(deg) at P1*
290700	6688685	45	45	*%UTM lon, lat, slopes(deg) at P2*
290725	6688845	45	45	*%UTM lon, lat, slopes(deg) at P3*
290720	6689100	45	45	*%UTM lon, lat, slopes(deg) at P4*
290690	6689340	45	45	*%UTM lon, lat, slopes(deg) at P5*
290630	6689500	45	45	*%UTM lon, lat, slopes(deg) at P6*
290500	6689680	45	45	*%UTM lon, lat, slopes(deg) at P7*
290040	6689750	45	45	*%UTM lon, lat, slopes(deg) at P8*

Figure 13 shows an example of excavation and mass filling in the sea close to Honningsvåg Airport. Note that this illustrates just an example of how the terrain modifications may involve both an excavation and a mass filling in the sea, the latter often being required in order to make possible both a runway extension as well as other infrastructure improvements.

This is a typical scenario when a Norwegian airport needs an extension of its runway due to increased air traffic and/or larger aircraft serving the site. Simulation of non-stratified airflow from the south-east is done and the resulting terrain-induced turbulence is shown in Figure 14, for the unmodified as well as for the modified terrain case. Here only minor differences are observed. However, an analysis of the aviation consequences by a specific terrain modification, needs several simulations with different atmospheric conditions in order to be complete. In that respect the climatology of the site must be taken into account in order to be as realistic as possible.

5 Usage of software tool

The software tool is a standard C++ code which, after being compiled and built, is used in command mode:

```
> edter -t tfile -p pfile
```

where *tfile* is the name of the file containing the terrain map description of the region encompassing the polynomial area to be excavated and *pfile* is the name of the file that contains the description of the polynomial region with its new elevation and its side edge slopes, as exemplified by Table 1. Presently, the *tfile* has to be given in

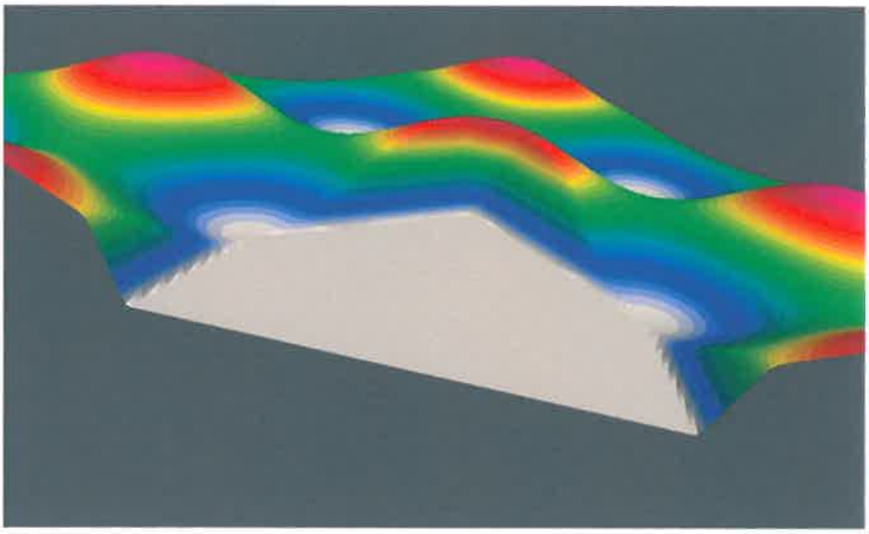


Figure 6: Excavation of a wavy sinusoidal terrain with multiple frequency in both directions. Slopes of sidewalls are 30 degrees.

vtk format (see [8]). The terrain modified output file is also a *vtk* formatted file.

6 Conclusion

Changes to topography in regions close to airports are quite often part of plans due to enlargement of built-up areas or due to improvements for aviation like for instance an extension of runways, as well as for other infrastructure improvements. Impact assessments with respect to potentially adverse atmospheric turbulence conditions are therefore needed before such plans are carried out. No specific rules seems to exist for these matters and consequence analyses case-by-case are therefore recommended.

In the present study focus has been on *terrain-induced atmospheric turbulence* close to airports. A numerical algorithm and software tool has been developed for the excavation of an arbitrary polygonal region within an area with a given topographic description. This tool has been tested on both artificial as well as on a couple of real terrains close to existing airports, with satisfactory results. The main benefits of the tool is its ease of use and flexibility to specify edge slopes along the sides of the polynomial region to be excavated. The polygonal vertices have to be given in UTM coordinates for the actual zone of interest, as given for the unmodified terrain.

Acknowledgment

The authors would like to thank Erling Bergersen and Avinor for the support and funding of research and development in the field of *terrain induced turbulence* modeling, analysis, and forecasting for aviation activities for many years.

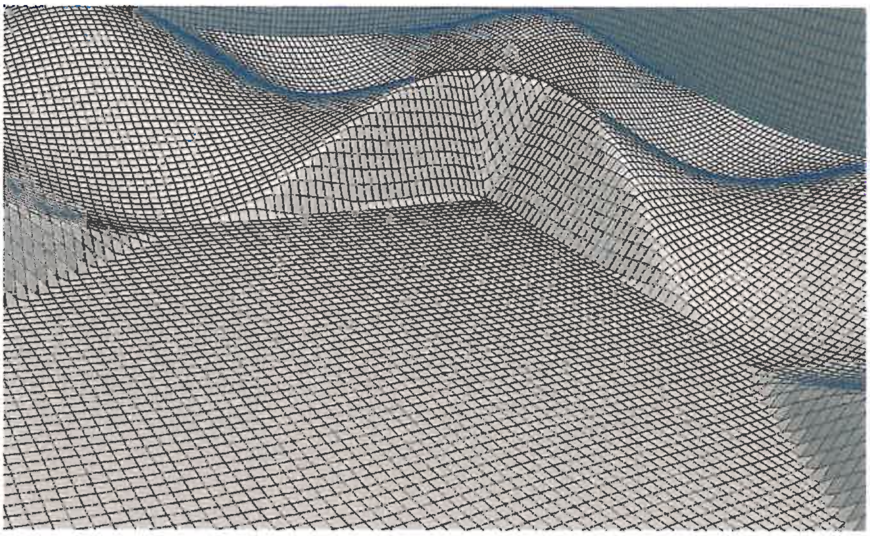


Figure 7: Excavation of a wavy sinusoidal terrain with a multiple frequency in both directions. It is the same case as Figure 6, but here the resulting structured quadrilateral surface mesh is shown. Note that the vertical dimension is scaled.

References

[1] J. O'Rourke, *Computational Geometry*, 2nd ed., Cambridge University Press, 2001.

[2] T. Utnes, Modelling of Stratified Geophysical Flows over Variable Topography, in *Geometric Modelling, Numerical Simulation, and Optimization*, G. Hasli, K-A. Lie. E. Quak, Springer Berlin Heidelberg, 2007, pp 361-390

[3] A.M.H. Nieuwpoort, J.H.M. Gooden and J.L. de Prins, *Wind criteria due to obstacles at and around airports*, National Aerospace Laboratory NLR, Technical Report NLR-TP-2010-312, 2010.

[4] A. Rasheed and K. Sørli, *Evaluation of the impact of the construction of a new harbour near Flesland Airport in Bergen*, September 2010, Technical Report SINTEF F16472, 2010.

[5] A. Rasheed and K. Sørli, *CFD Analysis of Terrain Induced Turbulence at Kristiansand Airport Kjevik*, Aviation, Volume 17(3), Taylor & Francis pp 104-112, 2013.

[6] A. Rasheed and K. Sørli and J.K. Süld and K.H. Midtbø, *Downscaling as a way to predict hazardious conditions for aviation activities*, Proceedings of the SESAR Innovation Days (2013) EUROCONTROL.

[7] `http://www.statkart.no/en/` Homepage of *Kartverket* (Norway).

[8] `http://www.vtk.org` Visualization Toolkit

[9] `http://www.ihs.com/products/industry-standards/org/icao/manuals/index.aspx` ICAO Manuals Collection

[10] `http://www.aci.aero/` Airports Council International Webpage

[11] `http://www.icao.int/safety/ism/ICAOAnnexes/Forms/AllItems.aspx` ICAO Annex 14

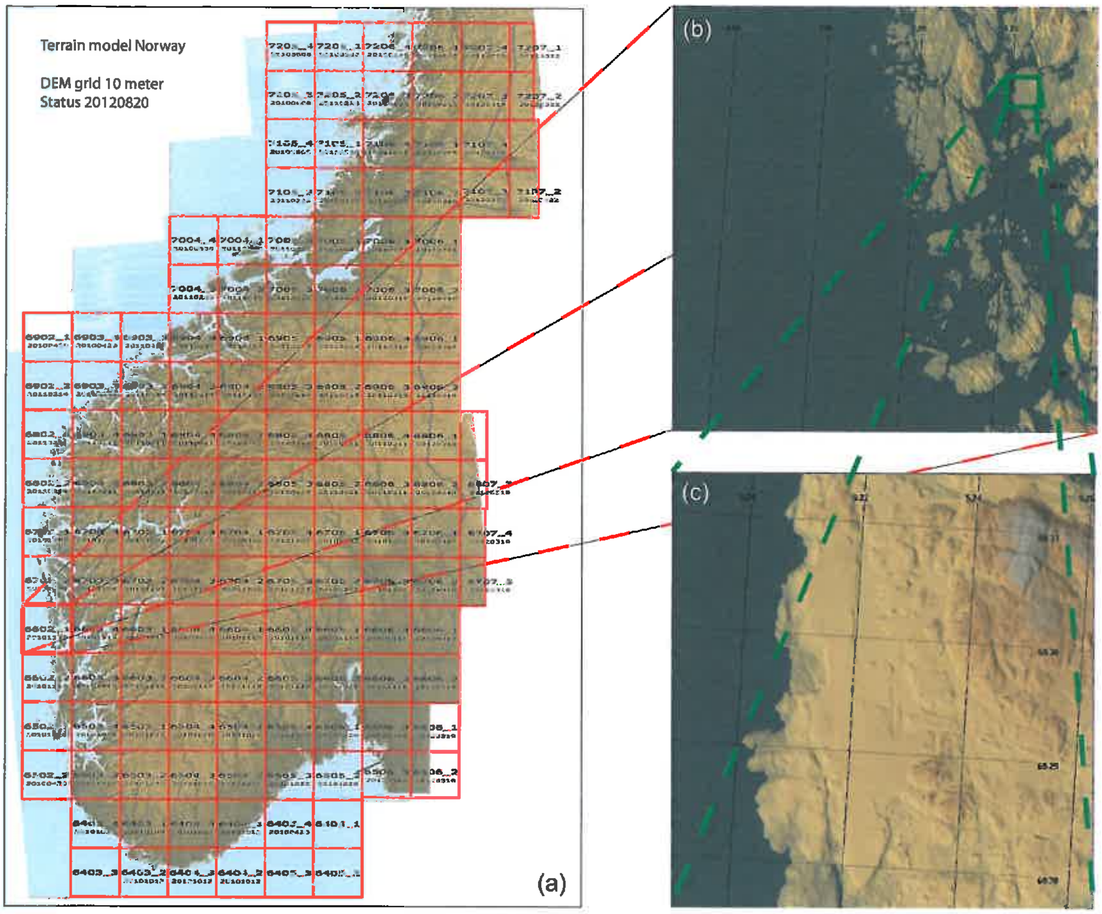


Figure 8: Zone 32 of the digital terrain of southern Norway with all its tiles (a). The tile containing the Flesland area is "outdrawn" (b) as well as a local area around the airport (c). Ref. *Statens Kartverk* [7].

Figure 9: Example of excavation and mass filling close to Bergen Airport Flesland. Google map.

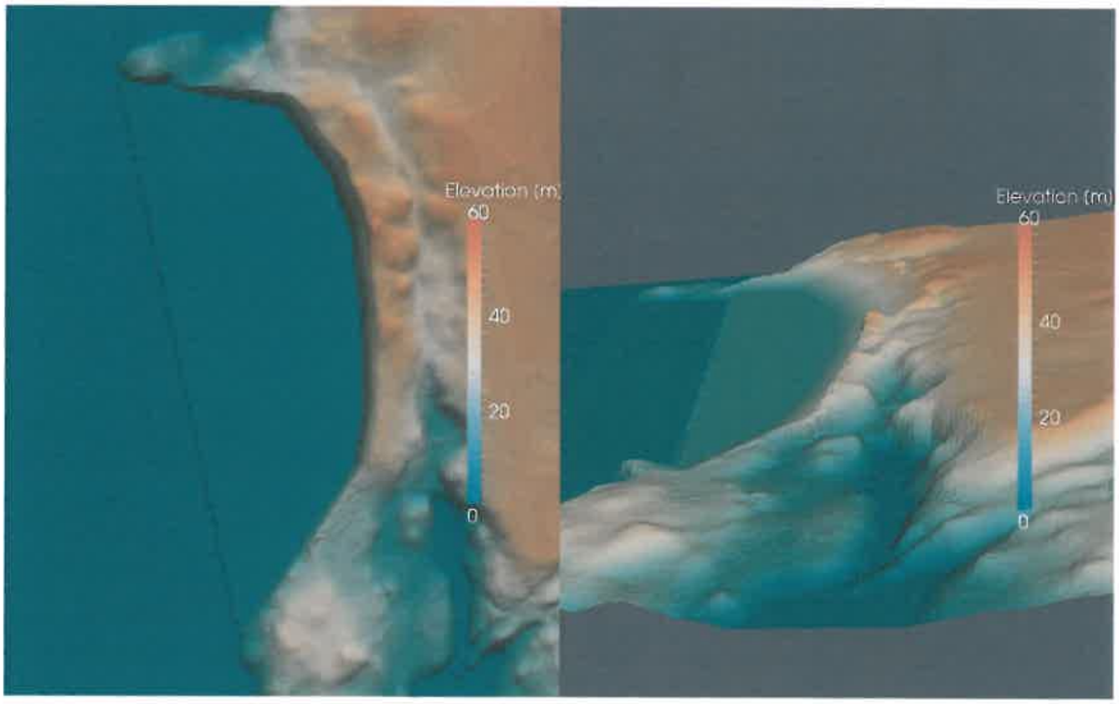


Figure 10: Excavated area by developed software based on the method described in Section 3. On the left is shown a harbour area at a single elevation, while the right side shows an example with two levels and an edge slope of 10° at parts of the edge facing the runway.

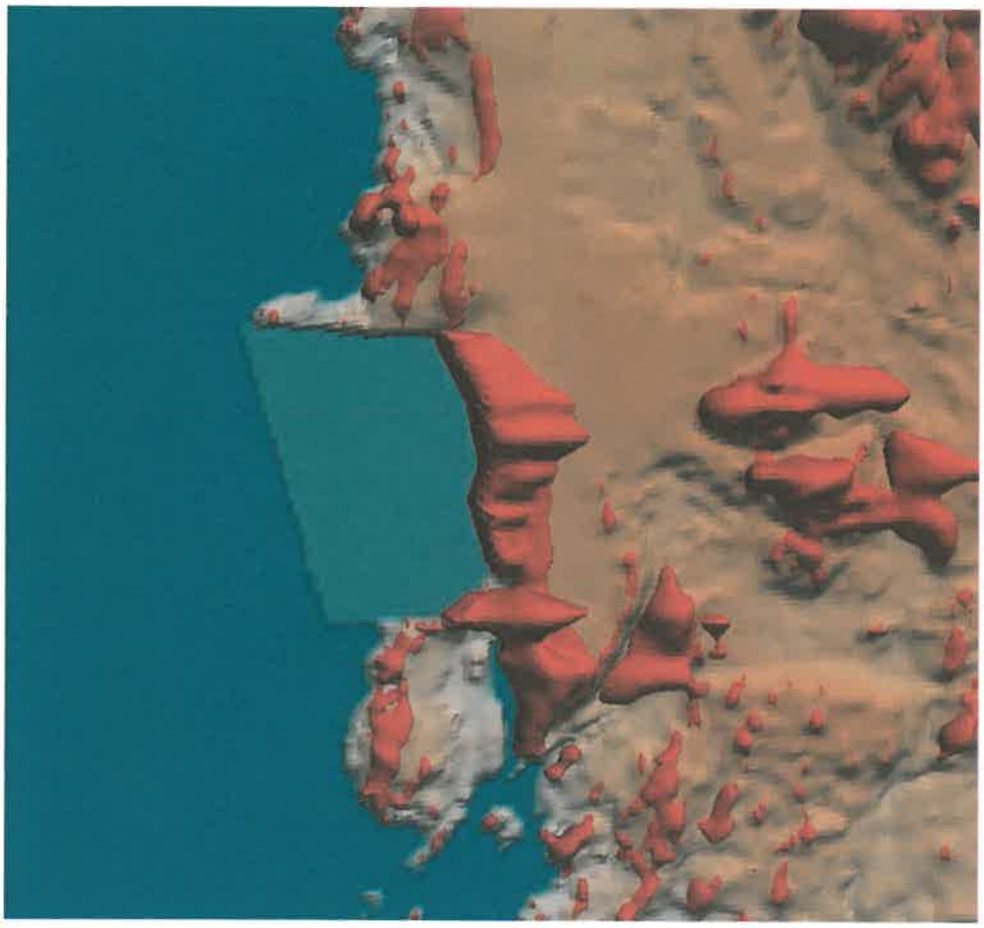


Figure 11: Example of impact assessment of an excavation and mass filling close to Bergen Airport Flesland. *Bird-view* of terrain and simulation results for turbulence intensity. The iso-surfaces of $ut = 3\,m/s$ are shown.

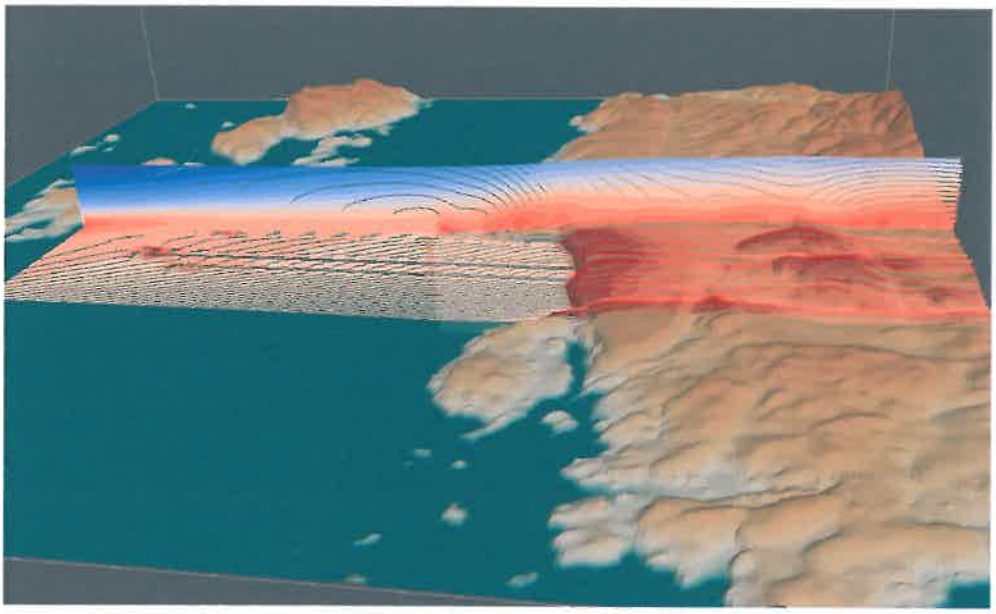


Figure 12: Example of impact assessment of an excavation close to Bergen Airport Flesland. A projective view of the terrain with airflow tracers and turbulence intensity.

Figure 13: Example of excavation and mass filling close to Honningsvåg Airport, Valan.

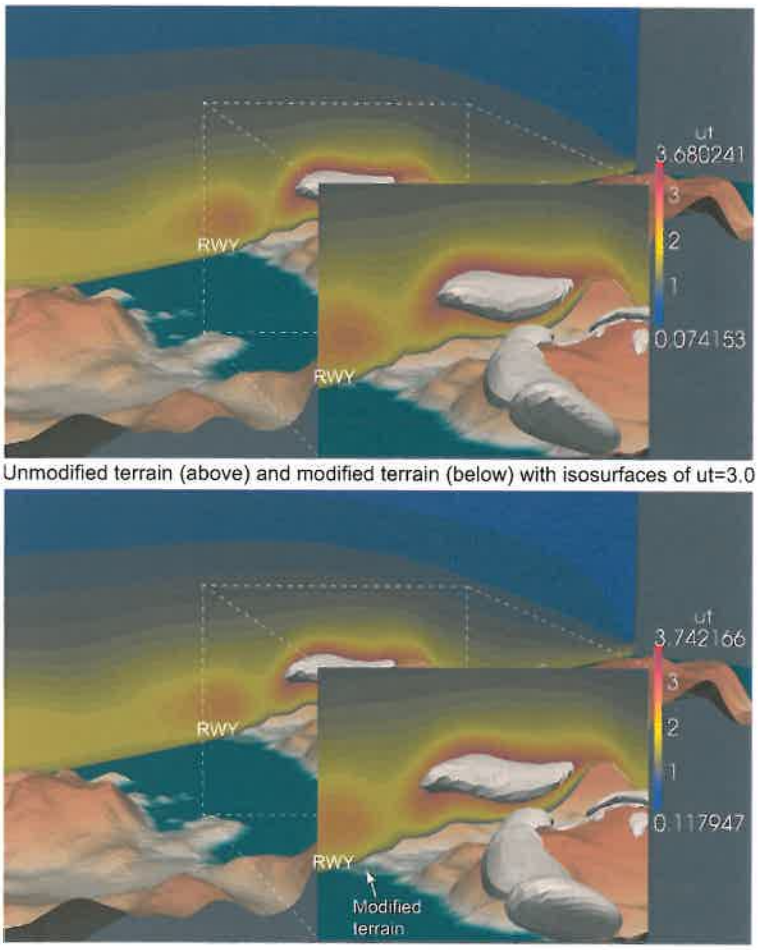


Figure 14: Example of impact assessment of an excavation and mass filling close to Honningsvåg Airport.

Technology for a better society
www.sintef.no