Wind tunnel measurement of surface wind conditions around buildings using the sand erosion technique

(M6: Wind tunnel measurement of flow in urban areas)

Márton BALCZÓ Ph.D.
assistant professor
Budapest University of Technology and Economics (BME)
Faculty of Mechanical Engineering
Department of Fluid Mechanics
Theodore von Kármán Wind Tunnel Laboratory

E-mail: balczo@ara.bme.hu

Introduction

It is a common observation of any urban resident, that buildings modify the flow and pollutant dispersion considerably. As an example the very high wind speeds are mentioned which can be experienced near the corner of large buildings in stormy weather (Fig. 1). Other locations in the urban space provide calm conditions despite the strong wind reaching the city. Another example about the influence of buildings is a so called street canyon, a high-traffic street bordered by multi-storey buildings from both sides. Pollutants released by the cars in a street canyon reach much higher concentrations compared to a road located in open terrain.

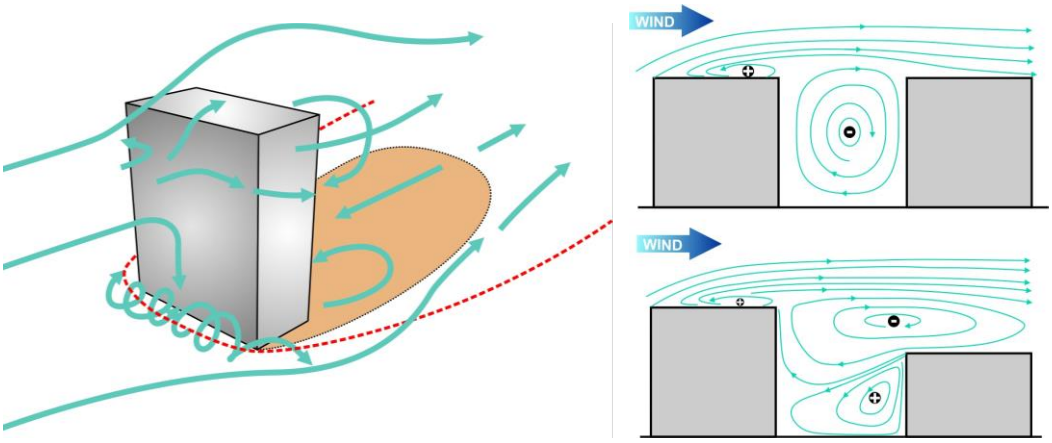


Fig. 1 Flow field around a tall building (Beranek and van Koten) Street canyons of different buildings.

The aim of this measurement is to visualize and quantify the distribution of the surface wind speed around a single building or around a group of buildings. As we will see, this distribution is highly inhomogeneous, and depends on the shape, height and density of the buildings.

Theoretical background

The atmospheric boundary layer

The wind which interacts with any manmade object on the Earth's surface has well defined characteristics. It is called the atmospheric boundary layer (ABL), also known as the planetary boundary layer (PBL), which is the lowest part of the troposphere and its behaviour is directly influenced by its contact with a planetary surface (Fig. 2). Its thickness varies with time and ground surface structure from a few 100 m to 5 km, and is typically 1-2 km. Heat, momentum, moisture and material transport between earth and atmosphere occurs in the ABL. Flow in the ABL is mostly turbulent, and mechanically or thermally induced vortices are responsible for the transport (turbulent diffusion).

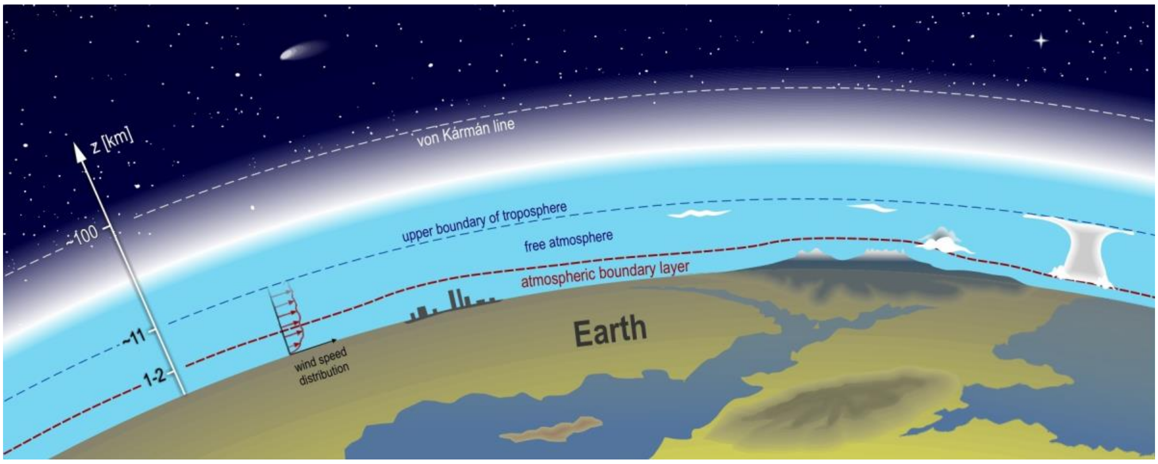


Fig. 2 A schematic view of the atmospheric boundray layer

According to Plate (1982) and Oke (2002), the ABL can be divided into several sublayers (Fig. 3). The functions and role of the sublayers are as follows:

- In the *surface layer* or *Prandtl layer*, meteorological variables change the quickest with height. The vertical fluxes of these quantities are approximately constant. Small scale turbulence caused by orography, vegetation and man-made structures plays a major role in the formation of this layer. Its thickness is about 10-20 % of the ABL. Over flat terrain (ice, grass) a laminar sublayer can exist very near to the surface. In urban regions, the surface layer can be further divided into:

- The *urban canopy layer*, in which flow and transport is determined by highly 3-dimensional, turbulent flow around and between the inhomogeneous arrangement of obstacles;
- The *roughness sublayer*, influenced directly by turbulent structures coming from surface obstacles, ranging from the average building height H up to 5H;
- The inertial sublayer, in which fluxes from the roughness sublayer appear already as horizontally homogeneous, consequently in which, ground surface can be approximated by a uniform roughness.

- In the *outer layer* (also called *Ekman-layer*) wind velocity is increasing to the wind speed of the free atmosphere. While in the lower layers Coriolis force has minor effect, with increasing flow velocity and decreasing friction, the influence of the Coriolis force from the Earth's rotation grows. As a consequence wind direction is changing by 20-40° in this layer.

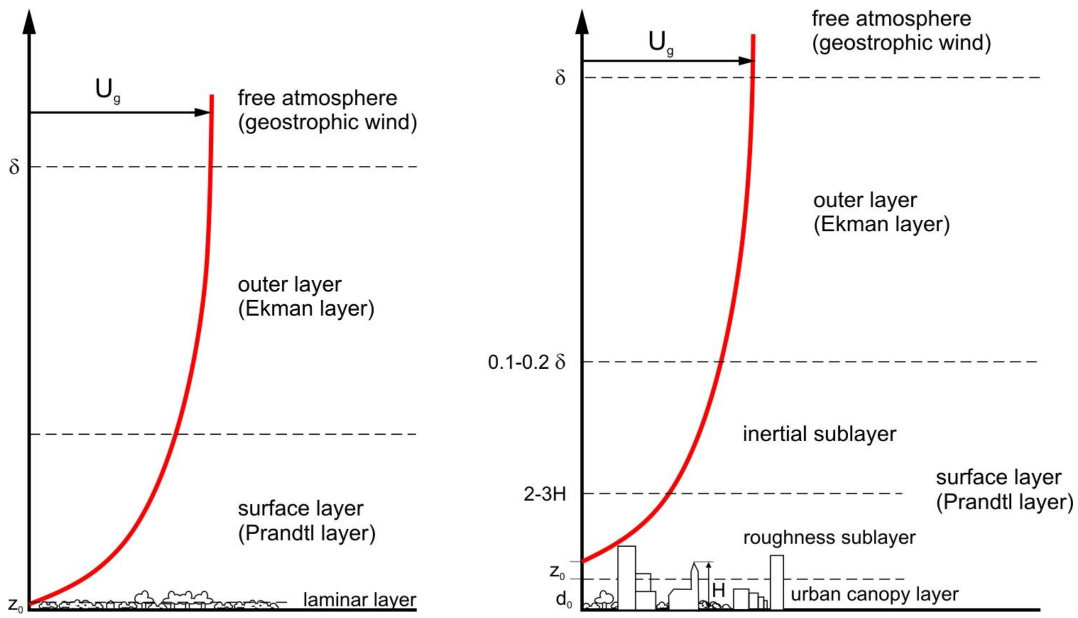


Fig. 1 Schematic mean wind speed distribution and sublayers of the atmospheric boundary layer. Left: the ABL above natural surfaces, right: the ABL above urban areas.

The constant momentum flux in the surface layer and the introduction of the mixing length approach allowed Prandtl (1932) to describe the *mean wind velocity profile* as a logarithmic function.

$$\frac{u(z)}{u^*} = \frac{1}{\kappa} \ln\left(\frac{z - d_0}{z_0}\right) \tag{1}$$

with:

κ - von Kármán constant, 0.41
d_0 - displacement height, describing the upward shift of the boundary layer due to dense built-up areas.
z_0 - surface roughness length, characterising the height and density of obstacles on the surface
u^* - friction velocity characterizing the shear stress τ between the layers

The empirical power-law function is also widely used:

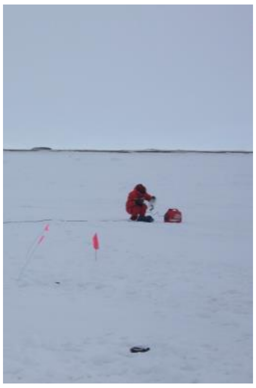
$$u(z) = u_h \cdot \left(\frac{z - d_0}{z_{ref} - d_0} \right)^{\alpha} \tag{2}$$

with:

α - power exponent,
u_{ref} - reference velocity at height z_{ref}.

As the surface type varies geographically on a wide scale, thus the size and intensity of vortices generated by the orography (mountains and hills), by the forests and vegetation and by manmade objects differ considerably. On-site, long-term measurement campaigns of the ABL allowed the classification of surface types and for the various surface categories, the typical values of the above mentioned boundary layer parameters could be summarised in various standards (Table 1).

Table 1 Surface categories and boundary layer parameters

				
	smooth	moderately rough	rough	very rough
	ice, snow, open sea	open grassland	suburban	urban
z_0 [m]	$10^{-5} – 5×10^{-3}$	$5×10^{-3} – 10^{-1}$	0.1 – 0.5	0.5 – 2
α [-]	0.08 – 0.12	0.12 – 0.18	0.18 – 0.24	0.24 – 0.4
d_0 [m]	0	0	0.75×h	0.75×h

Small scale wind tunnel modelling

Wind tunnels can be used to simulate the atmospheric boundary layer (This means, we generate a flow similar to the ABL in small scale) and building models aon the same small scale can be placed into the flow. This way, we are able to measure

- wind loading, forces and pressures acting on the building models

- investigate the flow field around buildings
- investigate the dispersion of a tracer gas (similar to that of air pollutants) around buildings, a group of buildings

Wind tunnels built specifically for this purpose are called ‘Boundary-Layer Wind Tunnel’. Fig. 3 shows the sketch of such a tunnel. Most important feature is a long flow preparation section, in which the incoming homogeneous flow is transformed into a boundary layer flow using spires (which generate huge vortices) and roughness elements (made of wooden blocks, paper cups, LEGO bricks)

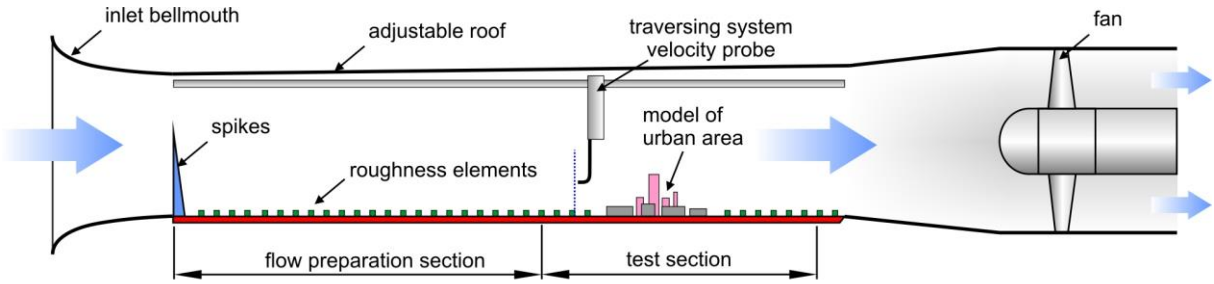


Fig. 2 Sketch of a boundary layer wind tunnel

The flow exiting the preparation section and entering the test section, where the building model is located, is already quite similar to the flow in the atmosphere. A certain type of ABL (e.g. urban ABL for the study of an urban building project) can be matched by variation of spire end roughness element size, shape and density.

Usually wind tunnel testing of scaled models requires keeping certain similarity criteria same as in full scale. For example, at low speed testing of aircraft models, the *Reynolds number* must be kept constant. This ensures that despite the different size, *the flow field is similar* in both cases. The Reynolds number is defined as:

$$\mathrm{Re} = \frac{u \cdot D}{\nu} \qquad (3)$$

with u – flow velocity , D – a characteristic length (size) of the object, ν – kinematic viscosity of the fluid.

In case of flow around buildings, to keep the same Re is not possible (at a model scale of 1:650 D_{model} = D / 650, thus one would require u_{model} = 650u which is not possible). However, in case of buildings with sharp edges, it is enough that Re > 2.10^4 and the flow above this limit will be similar to the full scale flow.

Sand erosion technique

Sand erosion technique is a useful semi-quantitative tool for estimating wind conditions on the ground. Before measurement the black painted model’s surface is covered by white sand of homogeneous corn size (Fig. 4). With step wise increase of the wind tunnel wind speed the sand is blown away, leaving the black surface to appear. The model is photographed from above at each velocity step, and contours of sand are digitized and assigned to the actual wind speed. With a calibration measurement beforehand, the method can give quantitative results.

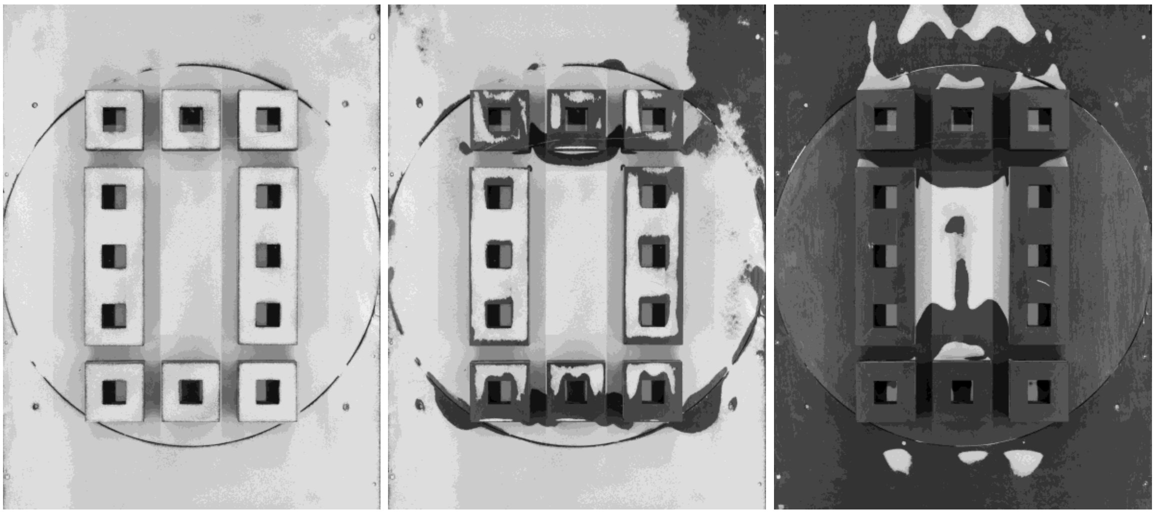


Fig. 3 Left: wind tunnel model in initial state, covered with sand. Centre and right: sand removed from the model at small and higher wind tunnel speed.

The method was first described by Beranek and van Koten (1979). Quantitative analysis was applied first by Livesey et al. (1990) using digital image processing of the photographs taken. Since then, the method was used in a number of studies: Rodrigo et al. (2012) investigated snow erosion and deposition around an Antarctic base in complex terrain. Conan et al. (2012) applied the method for wind resource assessment in a mountain area. Several researchers have shown that the entrainment of sand particles is a complex phenomenon, not only influenced by the average wind speed above the surface, but also by the gustiness of wind. According to Livesey et al. (1990), the sand erosion contour map is approximately proportional to the sum of the mean speed and its standard deviation. This is advantageous for wind comfort studies, as wind comfort is depending on a similar quantity. The very thorough study of Dezső (2006) on all aspects of this technique indicates that the transport of sand particles is influenced by several effects which increase the uncertainty of the method. Despite these concerns, high speed locations are very well shown by sand erosion, which makes this method suitable to a preliminary screening of a large investigation area to identify spots of interest, which can be later investigated by using more sophisticated measurement techniques.

Calculation of flow field from the sand erosion photographs

At the beginning, we performed a calibration measurement, in which a sand-covered black flat plate was placed in the ABL flow. Sand corn size was between 0.16-0.25 mm. Wind speed was measured using a Pitot tube, at 290mm height (u_{ref}). Wind tunnel speed was increased in small steps and in each step, after 1 min settling time, a photo was taken. The critical wind speed at which the sand on the plate was carried away, was u_{ref} = 8.13 m/s.

During the sand erosion testing of the square, wind tunnel speed and thus, reference wind speed u_{ref} will be also increased step-by step. Is the sand carried away at a lower reference wind speed means that the flow is sped up at that location, while if it is carried away only at a higher reference wind speed, it had to be slowed down. We can define the velocity speed-up ratio VSR which is the ratio of the wind speed at which sand is removed from a flat plate (8.13 m/s in our case) and of the wind speed at which the sand is actually removed.

$$VSR = \frac{8.13}{u_{ref}} \qquad (4)$$

Combining the areas which became black with increasing speeds allows us to draw a map of the velocity speed-up ration VSR, like in Fig. 5.

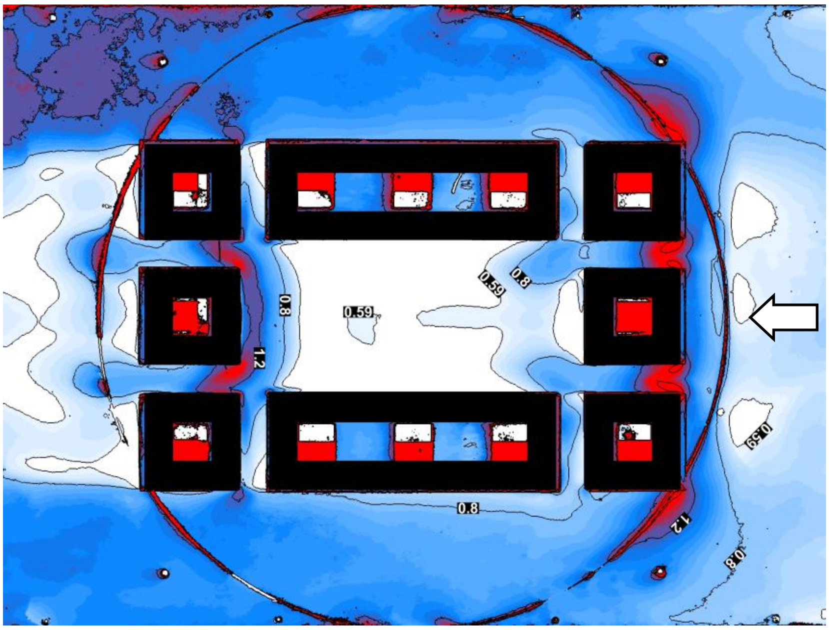


Fig. 4 Resulting composite image of Velocity speed-up ratio (VSR) post processed by the Tecplot data visualisation software. Red areas indicate high-speed zones (VSR is high), white areas indicate low spped zones (VSR is low)

The measurement setup

The wind tunnel

The wind tunnel experiments can be carried out in an NPL-type (Eiffel-type) wind tunnel with a closed test section of 0.5 × 0.5 m and 18 m/s highest velocity (Fig. 7). The test section has transparent windows, allowing access for photography. Between the inlet contraction and the test section spires and roughness elements are situated for the simulation of the atmospheric boundary layer (ABL). Wind speed can be adjusted by a 10-turn potentiometer (Fig. 8)

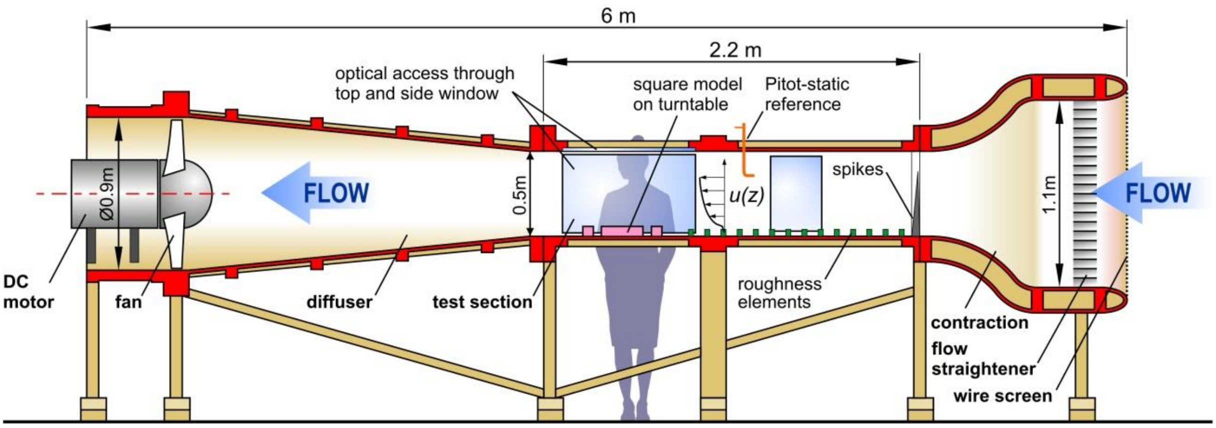


Fig. 5 The NPL type wind tunnel with its main components, and the measurement setup with the boundary layer generating elements and the wind tunnel model placed in the test section.

Fig. 6 Wind tunnel speed controller

Measurement of wind speed

The test section is equipped with a Pitot-static tube at 290 mm height,which is 180m in full scale if model scale is 1:650. Another Pitot static-tube is mounted on a vertical oriented linear drive, thus this probe can be moved in vertical direction. Pitot-static tubes are connected to EMB-001 handheld manometers to measure the differential pressures. Calculation of wind speed *u* from the measured pressure difference:

$$u = \sqrt{\frac{2 \cdot \Delta p}{\rho}} \tag{5}$$

with ρ – air density calculated from atmospheric pressure and temperature (for which measuring instruments are available in the lab) $\rho = p_0 / (R\, T_0)$, R = 287 J/kg K.

Boundary layer generation

A boundary layer *model* similar to the atmospheric boundary layer (ABL) is generated using spires and roughness elements. (Fig. 8)

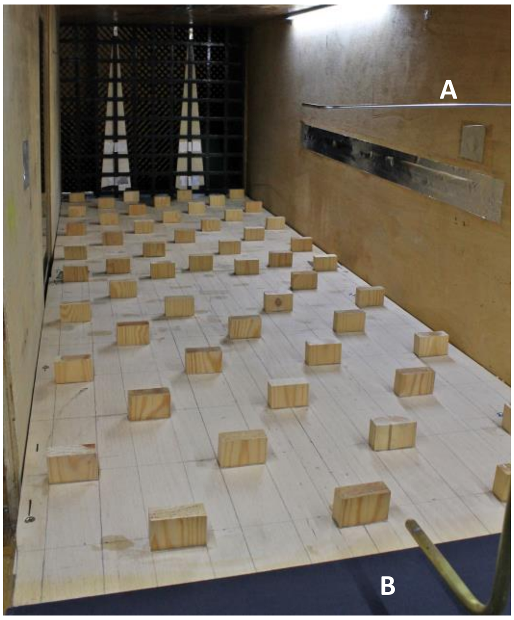


Fig. 7 Left: Boundary layer generation. A: reference Pitot-static tube (at z = 300 mm height) B: vertically traversed Pitot-static tube for velocity profile measurement. Right: EMB-001 Handheld device to measure differential pressures.

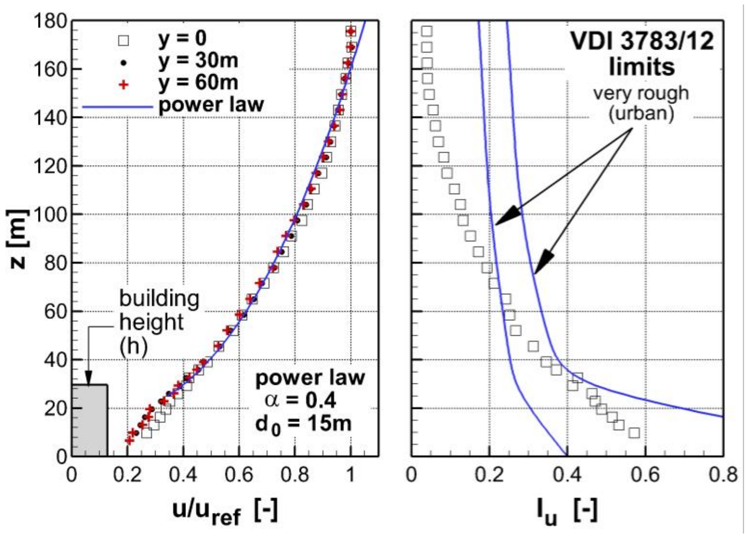


Fig. 8 Left: vertical profiles of dimensionless mean velocity ud of the approach flow at different offset distances from the symmetry plane (y = 0). Right: vertical profile of turbulence intensity Iu in the symmetry plane. Dimensions given in full scale

The generated boundary layer was checked in several vertical profile measurements. The results are depicted in Fig. 10, showing the boundary layer profile at different lateral offset from the mid-plane, with a power law curve fitted to it:

$$u(z) = u_h \cdot \left(\frac{z - d_0}{h - d_0} \right)^{\alpha} \tag{6}$$

where α is the exponent,
h is the reference height,
u_h is the mean velocity at the reference height and
d_0 is the displacement height.

The parameter α = 0.4 corresponds to very rough (urban) type surface according the VDI guideline 3783/12 (VDI, 2004). It must be noted that the profile is elevated with 15m (0.5*h*) off the ground which is proper in a densely built urban environment.

Turbulent intensity $I_u = \sigma_u(z) / \bar{u}$ (z) is also evaluated, and up to a height of 60 m full scale, the measured turbulent intensity profile falls within the limits of the VDI guideline.

The wind tunnel models

The models, like the one shown in Fig. 11, have a scale of 1:650 meaning that if the building height *h* is in full scale 30 m, then it is in model scale 46 mm. The model is located on a turntable of 0.5 m diameter. Thus, the incident wind direction can be changed by turning the table. Models are painted black. The surface must be clean (no remains of adhesive taps allowed) as any contamination will cause sand stick to the surface.

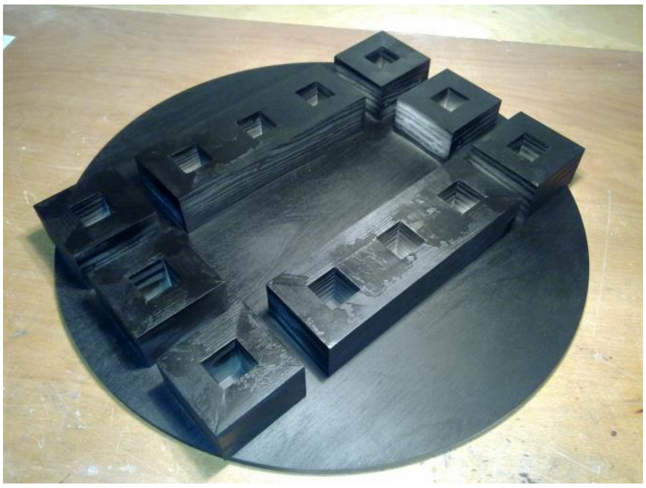


Fig. 9 Black painted model of an urban square on the turntable

Photo capture

The camera used is a Canon EOS 1100D DSLR camera (Digital single-lens reflex camera) with EF-S 18-55mm f/3.5-5.6 IS II lens. It can be controlled remotely using Canon's remote control software from the PC through an USB connection. Before the measurement, auto-focus is turned off, and image sharpness is manually adjusted (Fig. 12).

Photos are shot in aperture priority (AE) mode, aperture set larger than 5.6 to get high image sharpness. A long exposure (1/10 sec or longer) is no problem for us, as the sand image does not change in such a short time, and the camera support is mounted on an independent foundation not influenced by the vibration of the wind tunnel.

Fig. 10 Canon EOS 1100D DSLR camera

Test section illumination

When external light sources are used (e.g. spotlights outside the wind tunnel test section) reflections from the windows will disturb the photos. Thus, a distributed lighting (LED stripes) is installed inside the wind tunnel under the roof , which provide homogeneous lighting (Fig. 13, left). There is still some inhomogeneity left caused by internal reflections from the two side windows, as seen on Fig. 13, right.

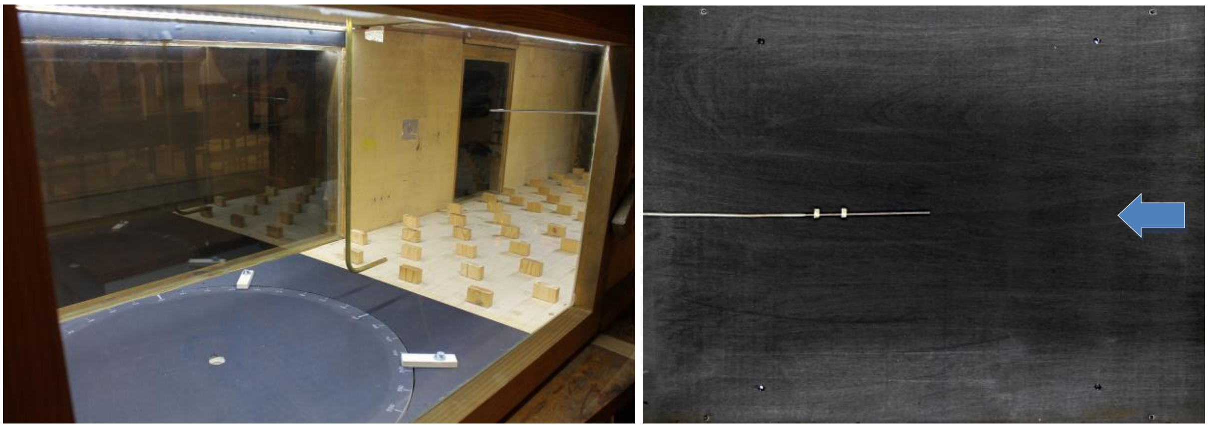


Fig. 11 Left: LED lighting in the wind tunnel. right: Check of light homogeneity using a black painted plate in the test section. (Image conrast was increased to make the differences more visible)

Camera adjustment

Sand erosion photographs must be taken from exactly vertical direction, centered exactly on the centre of the wind tunnel turntable (Fig. 13, Fig. 14, left). The adjustment can be made utilising the mirrored image of the camera itself on the top wind tunnel window. The mirror image has to be exactly in the centre of the turntable, and the turntable centre has to be in the middle of the photography. An adjustment sheet with printed scale can be useful for the accurate positioning.

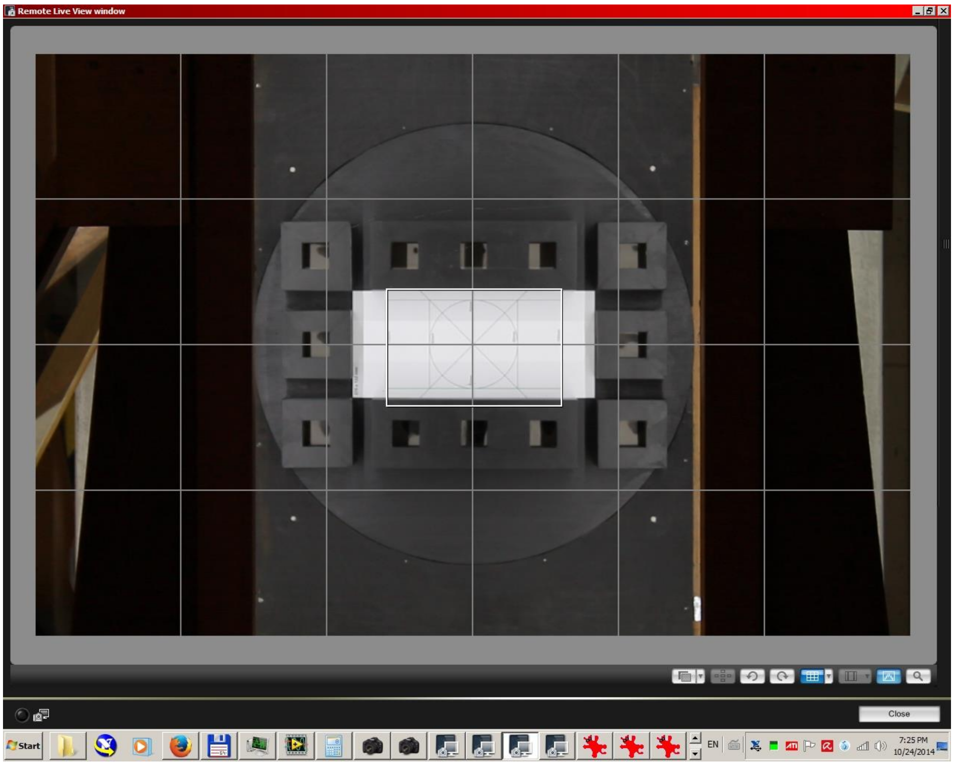


Fig. 12 The Remote Shooting window of the software showing perfect adjustement. An adjustment sheet was placed on the model.

To minimise distortions, the camera must be placed as far as possible from the model and a camera lens with long focal length must be used. Otherwise, the camera will not “see” areas near the vertical building walls. A trick to avoid this problem is to give vertical building walls a slight angle of 1-2°. This will not modify the flow field too much, but the camera is able to see the areas near the wall (Fig. 15, right). In the current measurement, the camera and camera stand are already adjusted.

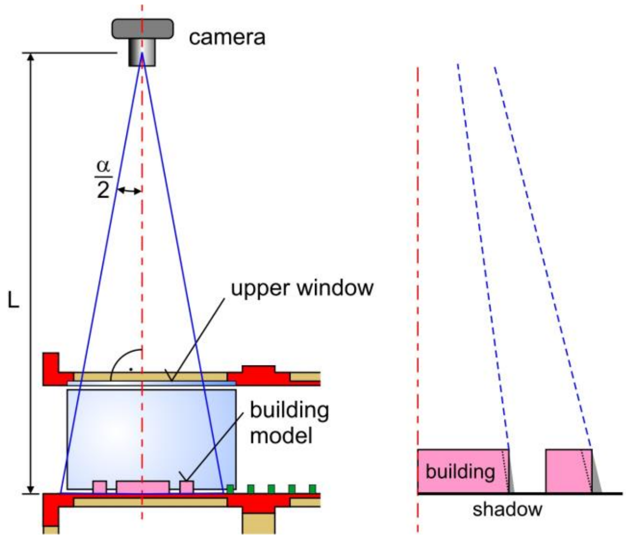


Fig. 13 Left: the proper setup of the camera above the model. Right: blind spots due to vertical walls. Dotted lines show the slanted walls to remove the blind spots.

Data postprocessing

Image conversion

Convert the captured sand erosion images to greyscale PNG files, and cut the unnecessary parts of the image e.g. using ***IrfanView*** or other image viewer tool. Batch processing tools can do that step at once for all of the images. All images must be exactly the same size.

The ARA Sand Erosion software

The program is able to subtract the selected background photograph pixel by pixel from the photograph taken during the sand erosion test, and convert the result into black and white images. As a result, only the areas covered with sand will appear in white, all other areas will be black. The conversion can be done in batch. To the individual photographs a scalar value can be paired which will be assigned to those areas of the actual photograph, which are black (from which sand is removed). This scalar value is the velocity speed-up ratio VSR. The composite photographic result shows the distribution of VSR with artificial colouring, which can be exported as a JPG file for inclusion in the lab report.

User steps

On the first ‘Images’ tab, select the directory with 8bit greyscale PNG sand erosion images. By clicking the file name in the listbox below, the program reads and draws the image. You can also add an image as background image (a photo without sand cover), and an image for adjustment (to determine the coordinate system transformation.)

The controls below the tabs give possibility to fit the image to width or height. Below the diagram, in the left corner, a toolbox appears. icons from left to right:

- turn on cursor mode (you are able to move a cursor on the image) by turning on cursor legend, you will see cursor ccordinates, and light intensity of the pixel the cursor is located at. By right clicking above the legend, you can bring the cursor to the center of the screen
- Zoom mode lets you zoom into areas of the image (useful at adjustment)
- Hand tool allows you to pan the image.

The colour scale on the right top corner can be adjusted. You can type the min and may values to be shown into the scale. You can also change colouring scale on the second tab 'B/W conversion'. On the second 'B/W conversion' tab you should experiment a bit with adjusting the parameters of the black & white conversion of the images. The subtraction of the background image helps to reduce light inhomogeneity. You can also subtract a multiple of the background (just 90% or even 130%) to decrease the lighting inhomogeneity of the resulting image. The other parameter to be adjusted is the B/W conversion threshold. Do that in a way that only areas covered by sand are white. Check more than one image of the measurement, if the conversion works well. By wrong settings, also areas not covered by sand will be converted to white (or vice versa), leading to falsification of the results. Such an error is shown in Fig. 17, left with red colour. In this case sand in the shadow of the buildings was not detected as it should as a white area, despite covered by sand.

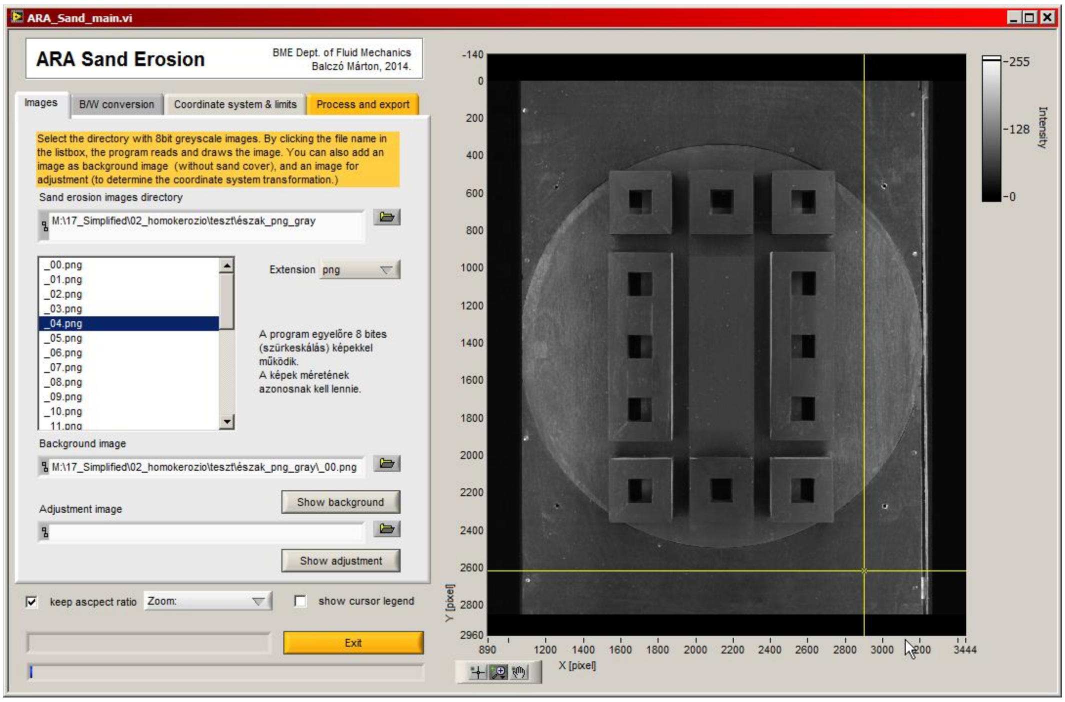


Fig. 14 Main window and ‘Images’ tab of the program.

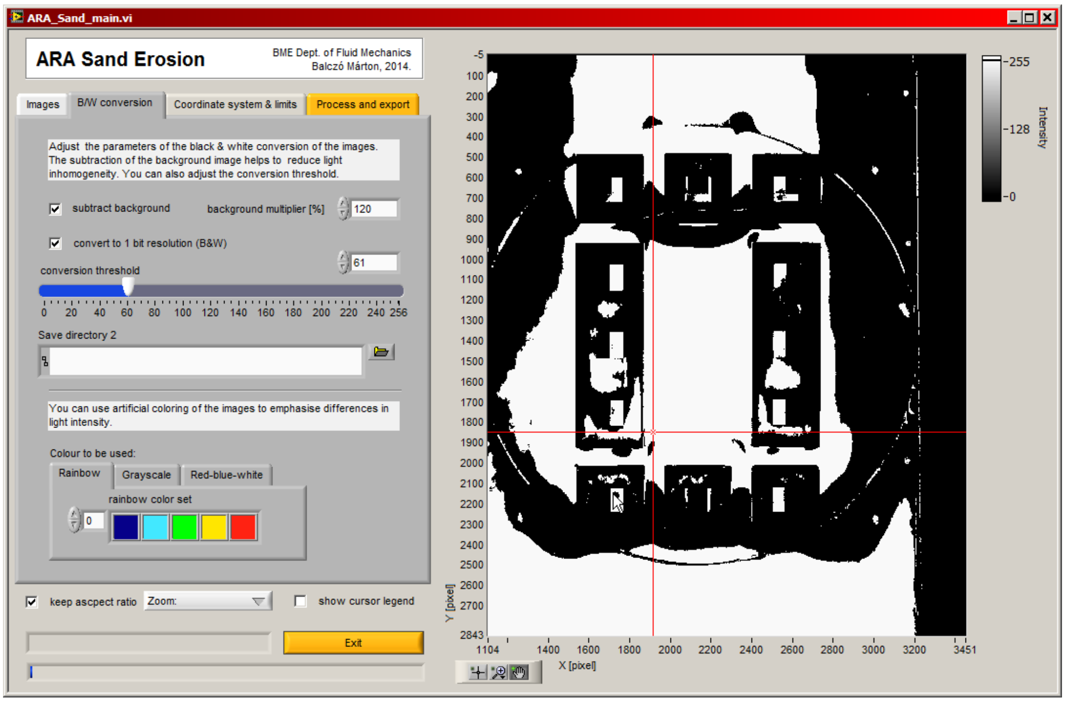


Fig. 15 ‘Black and white conversion’ tab and colour scale selection

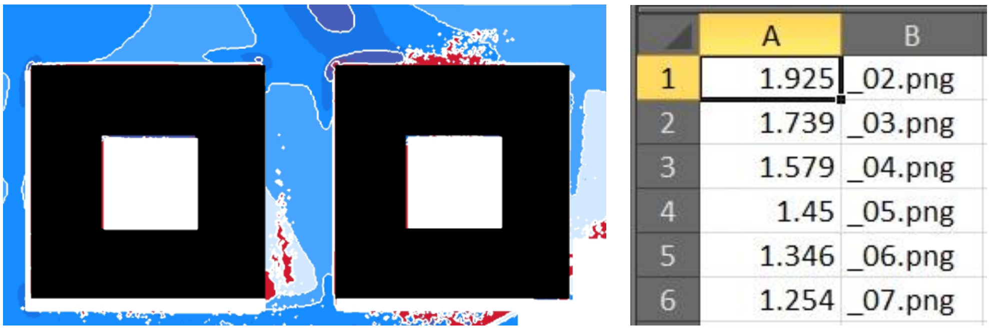


Fig. 16 Left: Conversion errors (red areas) in the composite photograph. Right: Generation of tab-sperated TXT file in MS Excel

The tab ‘Process and Export’ is the final step to generate the resulting composite photograph. Create and import a tab separated txt file with values which you want to assign to the black areas of the images in the 1st column (velocity speed-up ratio VSR), and with the file names of the images in the 2nd column. (Fig. 18, right).

Attention: In the text file, use period as a decimal separator!

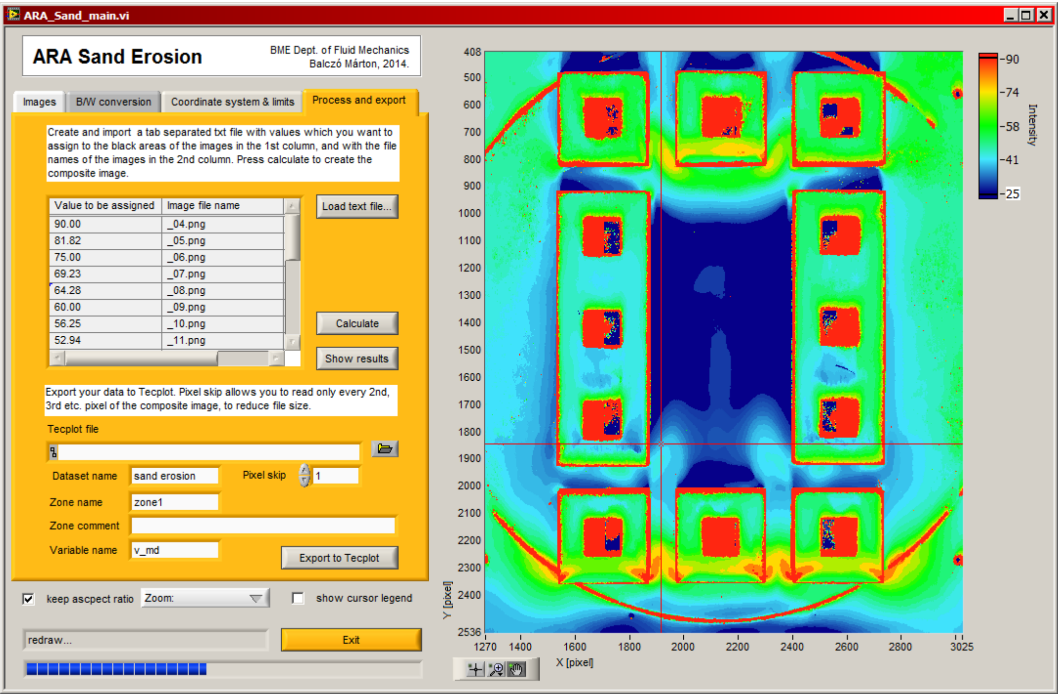


Fig. 17 Left: the ‘Process and Export’ tab of the program, right: A custom coloured composite image result

Press ‘Calculate’ to create the composite image. Then press ‘Show results’ to display it. By changing and adjusting the colour scale, you can highlight areas with different VSR. Press ‘Save image’ to export the data to an image file. Exporting to Tecplot data visualisation software is also possible.

Determining the coordinate system transformation between image and model

Image results are in an X-Y pixel coordinate system. The wind tunnel model has a different coordinate system, usually in mm scale and with different origin and angle. To determine the transformation between the two, we print an adjustment sheet with the model coordinate systemand place it on the model. We shoot the adjustment photo, and open it in the program. Now we select the coordinates of origin using the cursor. (Coordinates in pixels can be taken from the cursor). If you select another point, a reference coordinate on the sheet (e.g. 50mm, 100mm) and take the pixel coordinate of it, then the program calculates the scale and the rotation of the coordinate system tarnsformation.

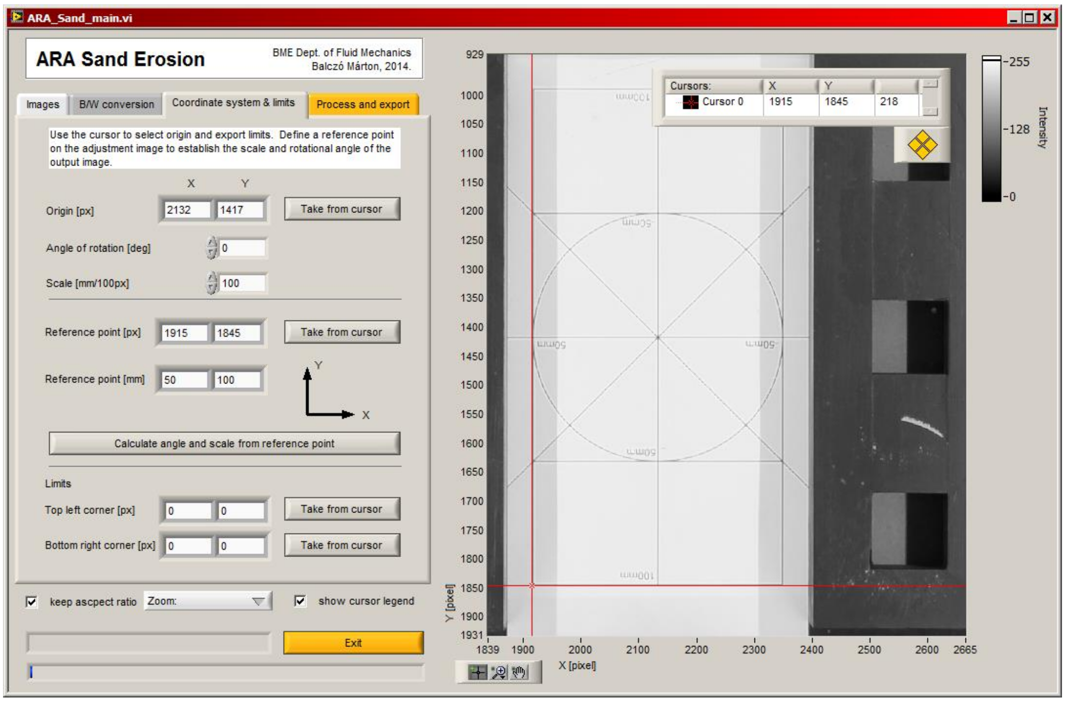


Fig. 18 The ‘Coordinate system and limits’ tab of the program, with the photo of the adjustment sheet.

Tasks during the measurement

1) Prepare sand of particle size 0.16-0.25 mm (or 0.25-0.315 mm) using the available fractional screening device.
2) Read the atmospheric pressure and temperature from the lab instruments
3) Place the boundary layer generation spires, the roughness elements and a flat plate in the wind tunnel
4) Connect the digital manometer to the reference Pitot-static tube.
5) Turn on the digital camera, and make yourself familiar with its use. Shoot background photographs; adjust camera aperture and shutter speed, ISO setting. Adjust external lighting (window screen and LED lighting)
6) Cover the flat plate with sand in a layer of ~ 1mm thickness
7) Close the test section doors and start the calibration test
8) By step by step increasing velocity determine the wind speed at which the sand is carried away from the flat plate. Keep 1 or 2 min settling time between steps.
9) After finishing the calibration measurement, place the model to be investigated into the test section. Set the required wind direction by turning the turntable.
10) Close the wind tunnel windows, and shoot an adjustment and a background photograph.
11) Cover the model with sand

12) Close the test section, and start the measurement. Increase wind speed step by step. After the settling time, shoot a photo, then increase the wind speed again. After the highest wind speed is reached, turn off the wind tunnel.
13) Remove the sand residuals, set another wind direction, or another building configuration, and repeat the procedure from 9) to 11)

14) Analyse your data:
15) Calculate VSR values to each photography captured, and create a tab separated TXT file.
16) Cut and convert all images to grayscale to a new directory for each wind direction or building configuration.
17) Perform the analysis using the ARA Sand Erosion software as described earlier.
18) Save your data.
19) Discuss the results with your supervisor.
20) At home, prepare the lab report.

Other helpful documents

[1] YouTube movie about the test: http://tinyurl.com/sanderosion1

[2] Manual for the EMB-001 handheld manometer

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