ESTIMATION OF THE FLOW CHARACTERISTICS BETWEEN THE TRAIN UNDERBODY AND THE BALLAST TRACK

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Abstract. *The purpose of this work is to estimate the equivalent roughness of the ground below the train, which consists of both ballast and sleepers. The motivation is that, in order to study the flow between the train and the ground utilizing a Reynolds Averaged Stress model, and to make a stationary analysis, the sleepers can not be treated individually and have to be considered as a part of the roughness of the ground.*
The flow under a train can be simplified in order to study the effect of the wall made up by sleepers and ballast. The easiest configuration to carry out this work is that corresponding to two-dimensional fully developed flow, in which periodic boundary conditions can be imposed at the entrance and exit. The Couette flow has been chosen, because it is the easiest one, and besides represents better the physics of the flow below the train. A k-ω closure model to simulate turbulence was used, and calculations were carried out with Fluent. The average velocity profile is estimated and this is fitted to a logarithmic profile, from which the average roughness is obtained. The influence of the configuration on the obtained values of the equivalent surface roughness is analyzed. The following parameters have been changed: height of the gap, Reynolds number, roughness of the upper wall. The equivalent roughness seemed to be insensitive, to variations of these parameters. The influence of the turbulence closure procedure on the results has been examined and different equivalent roughnesses are obtained, depending on whether the k-ω or k-ε closure procedure is used.
In order to estimate the validity of the whole profile across the gap, an analytic solution of the turbulent Couette flow (using the equivalent roughness for the lower wall) has been calculated. This analytic solution is obtained using either the k-ω or k-ε closure model; and it turns out to be the same, independently of which of the two models is used. The comparison between the analytic solution and the average velocity profiles is good. This analytical solution can also be of interest to estimate the shear stress in the ground that is related to the raise of the ballast. Comparisons between the analytical results for smooth walls with experiments and classical models for turbulent Couette flows have been also included.

1 INTRODUCTION

The flow under a train can be simplified in order to study the effect of the wall made up by sleepers and ballast. The easiest configurations to carry out this work are those corresponding to two-dimensional fully developed flow, such as Couette or Hagen-Poiseuille flows, in which periodic boundary conditions can be imposed at the entrance and exit. The Couette flow shown in Fig. (1) has been chosen, because it is the easiest one, and besides represents better the physics of the flow below the train; also, according to large eddy simulations carried out in our laboratory by Jiménez et al. [6], it reproduces well turbulence characteristics near the wall. Three sleepers are included, and the ground in between has the roughness corresponding to the ballast. The flow field is calculated for the configuration shown in Fig. (1); specifically, the velocity profiles for several positions are obtained, see Fig. (2). A k-ω closure model to simulate turbulence was used, and calculations were carried out with Fluent. The average velocity profile is estimated and this is fitted to a logarithmic profile, from which the average roughness is obtained. The calculations are repeated for several configurations of the sleepers, and the obtained roughness is compared with the values found in the literature, given in Jiménez [5].

In order to estimate the validity of the whole profile across the gap, an analytic solution of the turbulent Couette flow (using the equivalent roughness for the lower wall) has been calculated. This analytic solution is obtained using either the k-ω or k-ε closure model; and it turns out to be the same, independently of which of the two models is used. This solution is the same one obtained by von Karman [7], by postulating the existence of homologous turbulence. Its validity is discussed by Bech and Andersson [2], which carried out comparisons with databases originating from a direct numerical simulation. The comparison between the analytic solution and the average velocity profiles is good.

The obtained average profile is compared with the law of the wall and the analytic solution for the equivalent roughness. The origin of the vertical coordinate is chosen so that a best fit is obtained between the law of the wall and the average profile near the ground. This origin of the vertical coordinate turns out to be at the surface of the ballast.

The influence of the configuration on the obtained values of the equivalent surface roughness is analyzed. The following parameters have been changed: height of the gap, Reynolds number (by changing the velocity of the upper wall), roughness of the upper wall (in the initial configuration this wall is supposed to be smooth). The equivalent roughness seemed to be insensitive, to variations of these parameters.

The influence of the turbulence closure procedure on the results has been examined and different equivalent roughnesses are obtained, depending on whether the k-ε or k-ω closure procedure is used. Presumably, this is due to the way in which the two methods calculate the recirculation behind the sleepers. If the calculations are performed using an equivalent roughness the solutions obtained with the two closure methods are the same, and equal to the exact solution.

There are several authors performing work of a similar nature to the one carried out here. See for example Cui et al. [3], Ashrafian et al. [1], Leonardi et al. [8]. Their results are quantitatively and qualitatively similar to those obtained here. For previous works dealing with equivalent roughness of wall with steps, see the review by Jiménez [5].

Finally, comparisons between the analytical results for smooth walls with experiments and classical models for turbulent Couette flows have been included; although these comparisons are not directly related to the application and objectives of this work, they can be useful to validate the analytical model proposed for a turbulent Couette flow.

2 PROBLEM SET-UP

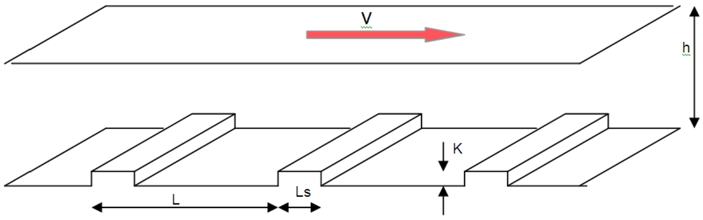


Figure 1. Configuration used for the calculations.

The basic configuration used for the calculation of the flow in the gap is shown in Fig. (1). As indicated before the main assumptions of the model are:

- Fully developed two-dimensional Couette flow.
- Most simulations have been made using RANS (k-ω), although comparisons with other closure models have also been made.
- Periodic conditions have been imposed at the outlet and in the inlet.
- The moving upper wall is assumed to be smooth (this has also been changed for comparison).
- In the lower wall there are alternating regions of sleepers and rough walls simulating the ballast. The sleepers are supposed to be smooth.
- For the roughness of the ballast region an equivalent roughness of k=0.04 m has been considered.

Data have been provided by Deutsche Bahn and SNCF, according to table 1.

Set of parameters	**h (m)**	**L (m)**	**Ls (m)**	**K (m)**	**V (km/h)**
Deutsche Bahn	0.40 0.38	0.62	0.127	0.04 0.02	275
SNCF	0.40 0.38	0.6	0.29	0.04 0.02	275

Table 1: Data used for the configuration of Fig. (1).

3 CALCULATION OF THE EQUIVALENT ROUGHNESS

A typical solution of the previous problem is given in Fig. (2), where the velocity profiles, corresponding to equidistant points along the channel, are shown. Details of the recirculation region after the step are also shown.

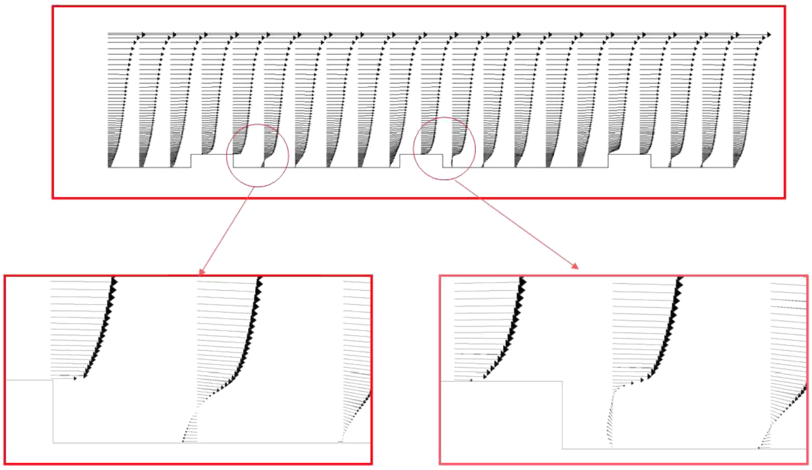


Figure 2. Velocity profiles in the gap, for the case k=0.04 m, Deutsche Bahn configuration.

The law of the wall for a fully rough wall can be expressed as:

$$\frac{u}{u*} = 2.5\ln\frac{z}{k_s} + 8.5 \tag{1}$$

where $u*$ is the friction velocity, z is the distance to the wall, and k_s is the equivalent roughness. In terms of wall units this equation can be rewritten as:

$$u^+ = 2.5\ln z^+ + B \tag{2}$$

where $u^+ = u/u*$, $z^+ = zu*/\upsilon$, where $\upsilon = 0.14\times10^{-4}$ m^2/s, is the kinematic viscosity of air, and consequently:

$$B = 8.5 - 2.5\ln\frac{k_s u*}{\nu} \tag{3}$$

It should be noticed that the introduction of the wall units is not really necessary, because the wall is fully rough and the process is independent of the kinematic viscosity of air. The calculation of k_s could be made directly from Eq. (1). Anyway, the wall units are normally used, and that is the reason to retain them here. The value of $u*$ is obtained from the total force over either of the two plates:

$$u* = \sqrt{\frac{F}{A\rho}} \tag{4}$$

where F is the force per unit width over either plate, A is the area per unit width of either plate, and ρ the air density. The non-dimensional value of the force over the plate, for each of the 4 cases indicated in table 1, is given in table 2, and it has been made non-dimensional with $1/2\rho V^2 h$. In table 2 the different contributions to the force in the lower plate are also shown, and it can be observed that the most important contribution is due to the pressure difference across both sides of the step. The value of k_s is then obtained from Eq. (3) in the form indicated before, and is given in table 3. In that table is also given the value of the roughness as used in geophysical applications, that is: $z_0 = k_s/30$. This alternative definition of roughness has the advantage that the term 8.5 in Eq. (1) is eliminated. Also, z_0 can be interpreted as the value of z for which u=0, so that:

$$\frac{u}{u*} = 2.5\ln\frac{z}{z_0} \tag{1'}$$

	K (m)	Pressure force		Wall shear stress		Total drag force	Pressure contribution
		Sleepers	Ballast	Sleepers	Ballast		
DB track	0.04	0.00536	0	6.335e-5	-2.335e-5	0.00540	99.26 %
	0.02	0.00419	0	0.000111	0.000334	0.00463	90.50 %
SNCF track	0.04	0.00547	0	0.000253	3.793e-6	0.00573	95.46 %
	0.02	0.00442	0	0.000342	0.000250	0.00501	88.22 %

Table 2. Calculated values of the pressure and shear stress contributions to the total force in the lower plate. The force is per unit width and is normalized with $1/2\rho V^2 h$

	K (m)	B	u* (m/s)	u*(m/s) eq. (18)	ks (m)	z_0 (m)	λ=K/L
DB track	0.04	-16.19	1.900	1.851	0.15	5e-3	0.065
	0.02	-11.85	1.726	1.701	2.89e-2	9.63e-4	0.032
SNCF track	0.04	-17.05	1.953	1.882	0.205	6.83e-3	0.067
	0.02	-14.28	1.824	1.784	7.258e-2	2.42e-3	0.034

Table 3. Equivalent surface roughness.

In Fig. (3) a comparison is made of the calculated values of k_s and the values found in the literature by Jiménez [5]. The solidity is the total projected area divided by the total surface area, and is also indicated in table 3. For the drag coefficient of the step, the value $C_D = 0.62$ has been chosen, based on the information obtained by Hoerner [4]. He gives a value of $C_D = 1.20 - 1.25$, for a two-dimensional obstacle, whose length in the direction of movement is of the same order as its heigth. The same value is also given by Jiménez [5]. However, for the cases considered here, the length of the sleeper is more than three times its heigth (see table 1). Despite not finding any values of C_D for such configuration, values of drag coefficient of similar rectangular two-dimensional objects in free flow have been extrapolated. For them, C_D decreases by a factor of 2, when the length is three times the height. It can be seen that there is a reasonable agreement.

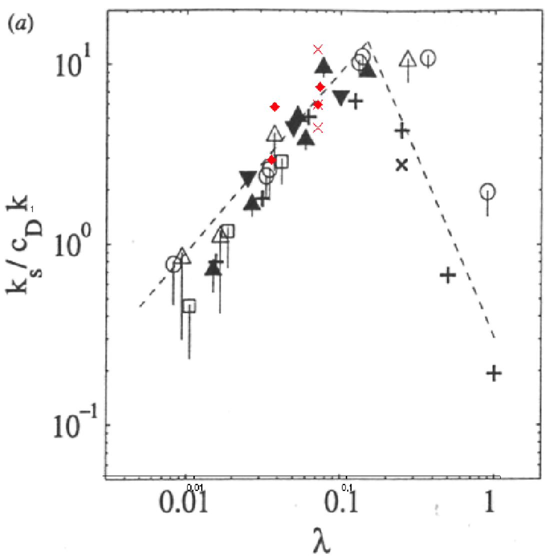


Figure 3. Comparison of the calculated values of k_s and those found in the literature by Jiménez [5]. The red points correspond to the calculations presented here. Crosses correspond to calculations performed with different closures, see section 5.4.

4 ANALYTICAL SOLUTION

An analytical solution for the turbulent Couette flow can be obtained. Each surface can be either rough or smooth. This solution will be useful for comparison with previous results, by substituting the sleepers and ballast by the surface with the equivalent roughness. The deduction will be made using the k-ε model, but an identical result will be obtained with the k-ω model.

The flow equations will be satisfied if the pressure and the shear stress are uniform across the gap. The shear stress will be given by ρu^{*2}:

$$u^{*2} = \upsilon_T \frac{\partial u}{\partial z} \tag{5}$$

Only the turbulent viscosity υ_T is considered, because the viscous sub-layer will not be resolved. According to the k-ε model:

$$\upsilon_T = C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

Where C_μ is a constant of the model. It can be easily shown that the value of k is constant across the gap. The equation for k (see for example Wilcox [11]) is:

$$0 = \frac{\partial}{\partial z}\left(\frac{\upsilon_T}{\sigma_k}\frac{\partial k}{\partial z}\right) + \upsilon_T\left(\frac{\partial u}{\partial z}\right)^2 - \varepsilon \tag{7}$$

The convective terms have been omitted because it is fully developed flow. The first term on the right represents turbulent diffusion, the second one production and the third one dissipation. Near each wall the following classical relation has to be satisfied:

$$k = \frac{u^{*2}}{\sqrt{C_\mu}} \tag{8}$$

If this constant value of k is substituted in Eq. (7) it can be seen, using Eqs. (5) and (6), that the production and dissipation terms cancel and the diffusion term will be zero, and that this equation is exactly satisfied.

The equation for ε (see for example Wilcox [11]) is:

$$0 = \frac{\partial}{\partial z}\left(\frac{\upsilon_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) + C_{\varepsilon 1}\upsilon_T\left(\frac{\partial u}{\partial z}\right)^2 \frac{\varepsilon}{k} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{9}$$

Its interpretation is as in Eq. (7) for k. The constants of the equation have to satisfy the following condition needed to satisfy the logarithmic layer (see Wilcox [11]):

$$C_{\varepsilon 2} - C_{\varepsilon 1} = \frac{0.4^2}{\sigma_\varepsilon \sqrt{C_\mu}} \tag{10}$$

In the logarithmic layer, near the lower wall the value of ε will be:

$$z \to 0, \varepsilon = 2.5\frac{u^{*3}}{z} \tag{11}$$

Similarly, near the upper wall:

$$z \to h, \varepsilon = 2.5\frac{u^{*3}}{h-z} \tag{12}$$

After using condition (10) and the Eqs. (5), (6) and (8), Eq. (9) becomes:

$$\frac{\partial}{\partial z}\left(\frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial z}\right)=\frac{0.4^2}{u^{*6}}\varepsilon^2 \qquad (9')$$

That integrated with the conditions (11) and (12), gives:

$$\varepsilon = 2.5\frac{\pi}{h}\frac{u^{*3}}{\operatorname{sen}\left(z\frac{\pi}{h}\right)} \qquad (13)$$

Substituting in Eq. (6) the turbulent kinematic viscosity will be:

$$\upsilon_T = 0.4u^*\frac{h}{\pi}\operatorname{sen}\left(\frac{\pi z}{h}\right) \qquad (14)$$

This result is equivalent to the one obtained by von Karman [7], by postulating the existence of homologous turbulence. The value of the velocity will be obtained by integration of Eq. (5), with the condition at the lower wall that

$$z = z_{01} \rightarrow u = 0 \qquad (15)$$

where z_{01} is the surface roughness of the lower surface as appears in Eq. (1'), $z_{01} = k_{s1}/30$. Then the velocity will be:

$$u = 2.5u^*\left(\ln\left(\frac{\operatorname{sen}\frac{\pi z}{2h}}{\frac{\pi z_{01}}{2h}}\right)-\ln\left(\cos\frac{\pi z}{2h}\right)\right) \qquad (16)$$

where the approximation has been made that $z_{01} << h$. The value of u^* is obtained by integrating up to the upper wall, where:

$$z = h - z_{02} \rightarrow u = V,\ \text{where,}\ z_{02} = k_{s2}/30 \qquad (17)$$

$$u^* = \frac{V}{2.5\left(\ln\frac{2h}{\pi z_{01}}+\ln\frac{2h}{\pi z_{02}}\right)} \qquad (18)$$

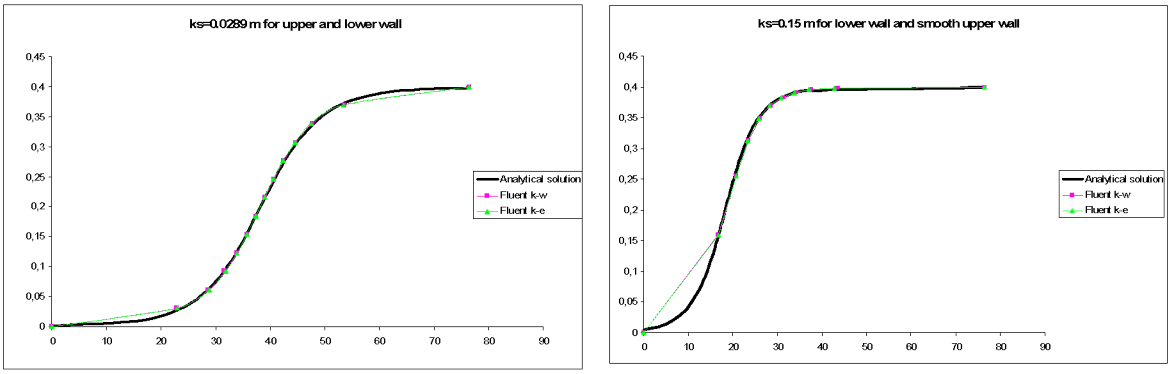
If a wall is smooth the value of z_0 will be given by:

$$z_0 = 0.113\frac{\nu}{u^*} \qquad (19)$$

Corresponding to using Eq. (1') and making B=5.45 in Eq. (2), which is the classical value of the law of the wall constant, for a smooth surface. In that case, Eq. (18) will be an implicit equation to calculate u^*. In table 3 are presented the values of u^* obtained from Eq. (18) using the roughness for the lower wall given in that table, and assuming that the upper wall is smooth. They can be compared with the values obtained in section 3 and given in that table, and it can be seen that the differences are smaller than 3%.

For given values of V, h, z_{01} and z_{02}, from Eq. (18) we obtain the value of u^* (and from Eq. (4) the value of the force on the plate), then, from Eq. (16) we obtain the velocity distribution between the plates. Eq. (18) can also be used to make a first estimation of the value of the shear stress, which is a parameter that is most probably related to the raise of the ballast. This equation very simply shows how the shear stress increases with the train velocity and the roughness of both the lower part of the train and of the track (including ballast and sleepers) and decreases with the width of the gap.

In Fig. (4) is represented this analytical solution for two typical cases, and compared with the numerical solution obtained with both the *k-ε* and the *k-ω* models using Fluent. The two curves corresponding to the numerical solution are undistinguishable and quite similar to the analytical solution. The larger differences correspond to the region near the walls where a straight line has been drawn to connect the wall to the next grid point that according to Fluent should be at a distance k_s from the wall; this will be discussed at the end of this paper.



(a) (b)

Figure 4: Comparison of analytical and numerical solution obtained with both the k-ε and the k-ω models using Fluent. (a) Both the upper and lower surfaces are rough with the same roughness k_s=0.0289 m. (b) The lower surface is rough with a roughness k_s=0.015 m, and the upper surface is smooth.

5 SENSITIVITY ANALYSIS OF THE RESULTS

The influence of the configuration on the obtained values of the equivalent surface roughness is analyzed. The following parameters have been changed: height of the gap, Reynolds number (by changing the velocity of the upper wall), roughness of the upper wall (in the initial configuration this wall is supposed to be smooth). The equivalent roughness seemed to be insensitive, to variations of these parameters.

The influence of the turbulence closure procedure on the results has been examined and different equivalent roughnesses are obtained, depending on whether the k-ε or k-ω closure procedure is used. Presumably, this is due to the way in which the two methods calculate the recirculation behind the sleepers. If the calculations are performed using an equivalent roughness the solutions obtained with the two closure methods are the same, and equal to the exact solution.

5.1 Influence of the gap between upper and lower plate

Calculations have been made with a much larger gap of h=3 m, maintaining the value of K=0.4 m and the DB track configuration. When applying the procedure indicated in section 3, the equivalent roughness turns out to be the same as when h=0.4 m, that is k_s=0.15 m, independently of the distance between the plates. In the case $h=0.3$ *m* the turbulent friction velocity is u^*=1.9 m/s, see table 3, and for h=3 m, u^*=1.515 m/s, that as expected is smaller. These values of u^* can also be checked with Eqs. (18) and (19).

5.2 Influence of the Reynolds number

Calculations have been made with a larger value of the upper plate velocity, V=350 km/h, and maintaining the value of K=0.04 m and the DB track configuration. When applying the procedure indicated in section 3, the equivalent roughness turns out to be the same as when V=275km/h, that is k_s=0.15 m, independently of the Reynolds number. There is a small difference in the velocity profile near the upper wall, which is smooth, and where viscous effects are more relevant. There is not a direct proportionality between $u*$ and V. For the case V=275 km/h, $u*/V$=0.0248, and for V=350 km/h, $u*/V$=0.0241. These values of $u*$ can also be checked with equations (18) and (19). These differences are very small, and do not influence the main conclusion, that the value of k_s is not affected by the Reynolds number.

5.3 Influence of the roughness of the upper wall

Calculations have been made with a rough upper plate, of roughness k_s=0.0289 m, and maintaining the value of K=0.2 m and the DB track configuration (see table 2). Thus the roughness of the upper wall should be equal to the calculated value for the equivalent roughness of the lower wall (table 3). The average velocity profile should then be anti-symmetrical with respect to the centre of the channel, and it is shown in Fig. (5). When applying the procedure indicated in section 3, the equivalent roughness turns out to be the same as when the upper wall was smooth, although the discrepancies between the law of the wall and the calculated average profile seem to be more apparent than when the upper wall was smooth. In Fig. (5) is presented a comparison of the average velocity profile and the law of the wall for the two cases: upper wall smooth and with a roughness k_s=0.0289 m. In the smooth case the turbulent friction velocity is $u*$=1.726 m/s, see table 2, and for the rough upper wall case, $u*$=2.812 m/s, that as expected is larger. These values of $u*$ can also be checked with equations (18) and (19), although they give slightly different values $u*$=1.70 m/s and $u*$=2.77 m/s, respectively. The two corresponding analytic solutions have also been included in Fig. (5).

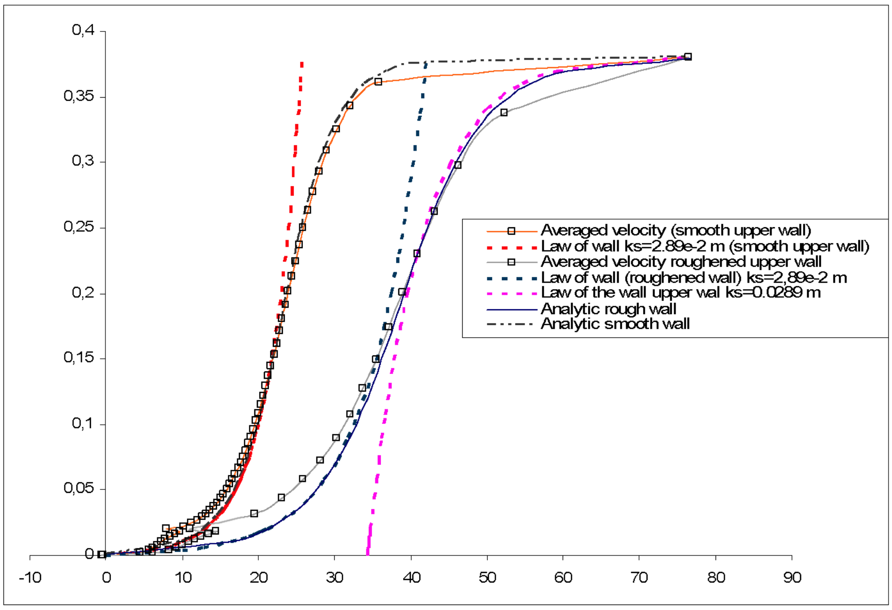


Figure 5. Velocity profiles with the upper wall smooth and rough, $k_s=0.0289$ *m*. Comparison with the different laws of the wall. K=0.02 m and the DB track configuration.

5.4 Comparison between turbulence models

The calculations for the case K=0.04 m and the DB track configuration have been repeated using the k-ε and k-ω (sst) (variant of k-ω proposed by Menter (see Wilcox [11])) models, using Fluent. The corresponding average velocity profiles are different and consequently they give different values of the equivalent roughness that are shown in table 4. However, the differences are not so important for the velocity profiles that depend on the logarithm of the roughness.

	k-ω	*k-ε*	*k-ω (sst)*
k_s (m)	0.15	0.39	0.10

Table 4. Values of the equivalent roughness obtained with the different models for the case K=0.04 m and the DB track configuration.

Taking these values in Fig. (3) with λ=0.065 and C_D=0.62 it is obtained that the one obtained with k-ω is closer to the results proposed by Jiménez [5]. According to this result and considerations for similar situations found in the literature, probably the k-ω is the most trustable model.

It should be remarked that when solving the problem with the equivalent roughness, and consequently without the steps due to the sleepers, the k-ω and k-ε, models solved with Fluent gave identical results. The discrepancies in the results of the different models must be due to the calculation of the recirculation regions behind the steps that are shown in Fig. (1).

5.5 Influence of the mesh resolution near the lower wall

Some of the equivalent roughness obtained are quite large, only somewhat smaller than the gap, and this may create a conflict in some commercial codes The calculations, carried out with Fluent and the equivalent roughness really confirm that for mesh sizes less than half the size of the equivalent roughness the solution obtained differs considerably from the exact solution. To check this, the case in which the sleepers are substituted by the equivalent roughness is solved numerically and compared with the average velocity profile, taking different cell sizes near the lower wall. This is shown in Fig. (6). For grid 1 the size cell size is 0.2 m, slightly larger than k_s. For grid 2, the cell size 0.1 m, and for grid 3, 0.05 m. The solution obtained with grid 1 is the same one given in section 3, which was identical to the analytical solution given in section 4. With grid 3, significant deviations are found, indicating that the solution is erroneous. It is surprising that an apparently normally behaving function, whose analytical solution is known, can not be obtained with enough numerical resolution.

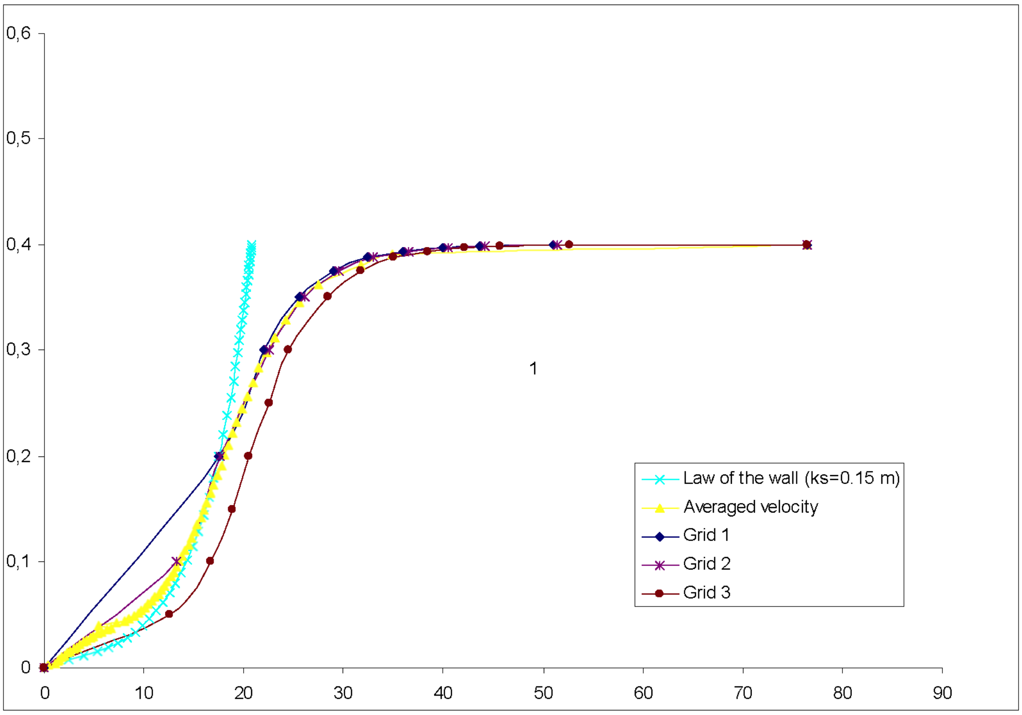


Figure 6. Velocity profiles calculated using an equivalent roughness for the lower wall. They are obtained with Fluent and using different grid sizes near the lower wall. For comparison are also presented the law of the wall, and the averaged velocity profile.

6 COMPARISON BETWEEN ANALYTICAL SOLUTION AND EXISTING MODELS IN THE LITERATURE FOR SMOOTH WALLS

The values obtained with the analytical solution proposed in section 4 have been compared with models and experimental data existing in the literature for turbulent Couette flows (Lund and Bush [8]), generally for smooth walls, so equation (19) is required. In Fig. (7), comparisons between experimental data taken from Reichardt [9] and the analytical solution for three different Reynolds numbers are included. It can be seen that the agreement is good enough, for high Reynolds numbers; probably for lower Reynolds numbers the effect of the laminar sublayer, neglected in this analysis, would be important. In Fig. (8) the value of the friction coefficient, given by $2u^{*2}/V^2$, as function of the Reynolds number, obtained with the analytical solution proposed in section 4 (equations 18 and 19), is compared with the more complex asymptotic model developed by Lund and Bush [8] for a turbulent Couette flow with smooth walls. It can be checked that both curves are almost coincident. Besides, the agreement between this asymptotic model and experimental data of the literature is excellent

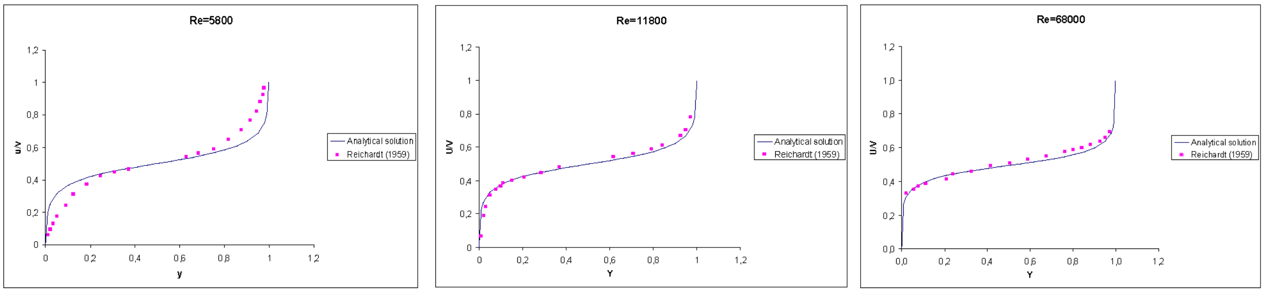


Figure 7. Comparison of the analytical solution and experimental data of Reichardt (1959) for a Reynolds number equal to (a) 5800, (b) 11800 and (c) 68000.

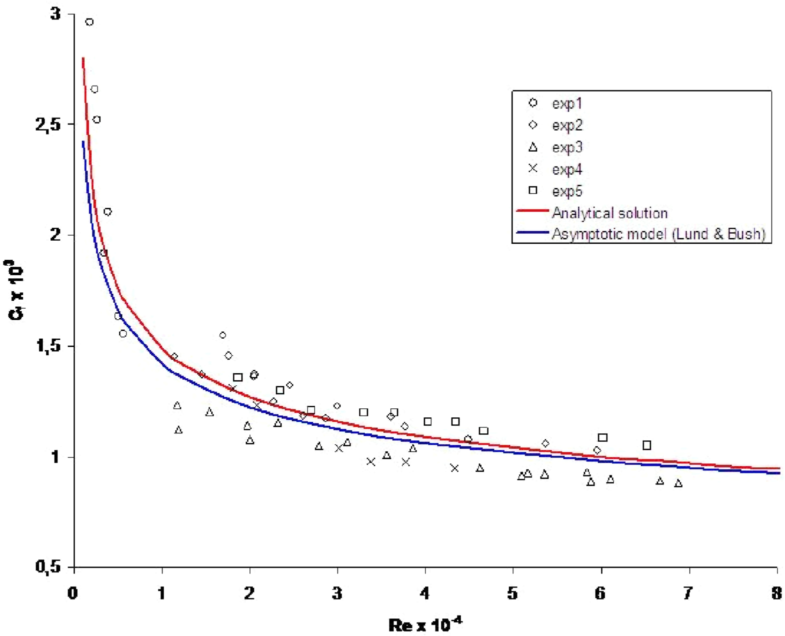


Figure 8. Comparison of the friction coefficient obtained with the analytical solution (section 4) and the corresponding one obtained with the asymptotic model proposed by Lund and Bush (1980). Experimental data of the literature are also included for comparison.

7 CONCLUSIONS

A procedure has been implemented to estimate the equivalent roughness of the ground below the train, which consists of both ballast and sleepers. The calculated values of the equivalent roughness are similar and have similar tendencies to others found in the literature. The flow fields obtained with the equivalent roughness and those obtained with the real ground (ballast and sleepers) show similar behaviours at a certain distance above the ground. The results do not depend significantly on the geometric configuration, or the Reynolds number, but have important variations depending on the turbulence closure method used; it has been estimated that the k-ω is the most appropriate one. An analytical solution of the turbulent Couette flow (using the equivalent roughness for the lower wall) has been calculated; it reproduces exactly the numerical solutions, except near the wall, and at distances of the order of or smaller than the equivalent roughness, where the numerical solution fails. This analytical solution can also be used to make a first estimation of the value of the shear stress, which is a parameter that is most probably related to the raise of the ballast. This analytical solution shows a reasonable agreement with preliminary experimental data of velocity in the gap between the train and the ground, obtained from a private communication; the agreement with more controlled experimental data in laboratory for smooth walls is quite good.

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