# Impact of Vegetation Density on Flow Characteristics in a Straight Compound Channel

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## ABSTRACT

**Vegetation exists on the floodplains of almost all natural channels. This vegetation results in a number of changes in flow features of open channel flows. Sometimes vegetation also exists within the main channel. This paper presents a numerical study in which the impact of vegetation density on different flow features has been considered. The variables investigated included velocity profiles, bed shear stresses, Reynolds stresses and side wall shear stresses. A compound channel with floodplain on both sides of the main channel has been considered. Four different vegetation densities were considered in this work. It was revealed that increase in vegetation density results in a decrease in the velocity values close to the bed and in the upper regions of the flood plains. The Reynolds stresses were also influenced considerably in the lower regions of the channel. Similar patterns were observed in case of bed shear stresses. The vertical profiles of side wall shear stresses were also investigated in this work. Such an investigation will help in enhancing the understanding and improving different conveyance and flow resistance calculation formulae.**

**Key Words:** **Vegetation, Compound Channel, Velocity Profiles, Wall Shear Stresses, Reynolds Stresses.**

## 1. INTRODUCTION

Vegetation exists in open channels. The large sized trees and bushes are spread all over the floodplains. Alongside these large vegetation elements, grass and other small sized elements are also present in the floodplains. The vegetation can be categorized mainly into two components. One is the flexible vegetation and other one being the rigid vegetation. The flexible vegetation includes grass and other flexible (bending) plants whereas rigid vegetation include stiff plants which do not bend when water passes through them such as different types of trees. Similarly vegetation existence differs from case to case. That is in one case it might be on the flood plains only, while in the other case it might be both on the banks and floodplains. In some situations the vegetation is sparse while in other scenarios, it is very dense. Sometimes vegetation also exists in the shape of patches within the main channel and on the floodplains. All these things impact the features of the water flowing through the open channels. The non-consideration of vegetation in conveyance calculation formulas will ultimately result in wrong calculation of discharge value and this will cause flooding and poor

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management of flood protection works. Therefore, it is essential to understand the physical changes in flow characteristics which occur due to the presence of vegetation.

The presence of vegetation considerably disturbs the flow characteristics because flow resistance is changed in the regions covered by the vegetation. The vegetation results in a drag force exerted by vegetation elements on the water flowing through the channel. The stems of vegetation generate turbulence and cause energy loss which slows down the mean velocity of flow. The flow patterns within and above the vegetative regions are greatly influenced by this drag force. This can be explained by the mixing layer analogy and two layer theory [1-2]. If the vegetation is highly submerged, then its behavior will be just like that of a channel with very high roughness.

The study of vegetated open channel flows is a major research area. A lot of work has been done in this field but still a lot is to be done. Notable research work in this area includes the following. Yang, et. al. [3] investigated the impact of submerged flexible vegetation in shallow open channels. Rigid vegetation has been investigated by numerous researchers such as Tsujimoto, et. al. [4] and Stone, et. al. [5]. The research work on flexible vegetation includes that of Wilson, et. al. [6] and El-Hakim, et. al. [7]. All of these researchers made their investigation experimentally. They explored different flow characteristics (such as primary and secondary velocity distributions, turbulent kinetic energy and its dissipation rate, boundary shear stresses, Reynolds shear stresses etc.) in the presence of vegetation. Several studies focused on velocity fields and turbulent flow structures [8-9]. Jarvela, [10] investigated a flow case with vegetation covering both the channel banks and floodplains. As far as numerical modeling is concerned, a number of researchers have also used this technique to investigate the flow changes under the influence of vegetation. Choi, et. al. [11] used Reynolds stress model to simulate the vegetated open channel flows. Recently Stoesser, et. al. [12] and Cui, et. al. [13] used LES (Large Eddy Simulation) to investigate the vegetation cases in open channels. Kang, et. al. [14] simulated partly vegetated cases using CFD (Computational Fluid Dynamics) technique.

This paper presents a numerical simulation work for getting the impact of vegetation density on flow characteristics. The vegetation exists on floodplains only. A three dimensional computational code has been used for this purpose. The results were presented in the shape of profiles for main velocity, Reynolds stresses, bed shear stresses and side wall shear stresses. The section two gives a description of fundamental equations and numerical setup. The section three contains results and discussion of the simulation work. It was followed by conclusion and acknowledgement.

## 2. VEGETATION MODELLING

The CFD code used here is based on continuity and Reynolds-averaged Navior-Stokes equations which form the basis of all the CFD models. These equations can be written as:

Continuity equation

$$\frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

The 3D (Three Dimensional) Navior-Stokes equations are as:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + \rho f_x + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho vu)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \rho f_y + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho wu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}= -\frac{1}{\rho}\frac{\partial P}{\partial z}+\rho f_z+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

The Reynolds-Averaged Navior Stokes equations are as follows:

$$\bar{u}\frac{\partial\bar{u}}{\partial x}+\bar{v}\frac{\partial\bar{u}}{\partial y}+\bar{w}\frac{\partial\bar{u}}{\partial z}=-\frac{1}{\rho}\frac{\partial\bar{P}}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\left(\frac{\partial\overline{u'^2}}{\partial x}+\frac{\partial\overline{u'v'}}{\partial y}+\frac{\partial\overline{u'w'}}{\partial z}\right) \tag{5}$$

$$\bar{u}\frac{\partial\bar{v}}{\partial x}+\bar{v}\frac{\partial\bar{v}}{\partial y}+\bar{w}\frac{\partial\bar{v}}{\partial z}=-\frac{1}{\rho}\frac{\partial\bar{P}}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\left(\frac{\partial\overline{u'v'}}{\partial x}+\frac{\partial\overline{v'^2}}{\partial y}+\frac{\partial\overline{v'w'}}{\partial z}\right) \tag{6}$$

$$\bar{u}\frac{\partial\bar{w}}{\partial x}+\bar{v}\frac{\partial\bar{w}}{\partial y}+\bar{w}\frac{\partial\bar{w}}{\partial z}=-\frac{1}{\rho}\frac{\partial\bar{P}}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\left(\frac{\partial\overline{u'w'}}{\partial x}+\frac{\partial\overline{v'w'}}{\partial y}+\frac{\partial\overline{w'^2}}{\partial z}\right) \tag{7}$$

where $P$ is the pressure, $v$ and $\rho$ are the kinematic viscosity and density of the water, $u,v,w$ are instantaneous velocities in $x,y,z$ directions, $t$ is time, $f_x,f_y,f_z$ are body forces, the over bar indicates the average of all the instantaneous components, $u_iu_j$ are the Reynolds stresses which result from the decomposition of instantaneous velocities into their mean and fluctuating components.

For validating the numerical results, the experimental data available in literature was used. The work done by the Nezu and Onitsuka [15] has been used for this purpose. They used a partly vegetated open channel with a bed slope of 1/2700, width of the channel was 0.4m. The rigid cylinders were used for representing the vegetation. The water depth used was 0.07m which resulted in an aspect ratio of 5.71. The validation process has been shown in Fig. 1.

The problem was solved using three dimensional numerical code FLUENT 12. The mesh used in this work was an unstructured mesh. The Gambit software was used as a mesh generator. The mesh was comprised of triangular elements. A pave scheme was used for meshing the faces. As far as vegetation is concerned, it was modeled with the help of circular elements. The mesh independence was checked and results of normalized stream-wise velocity obtained from existing mesh were found to be mesh independent. For this purposes, three meshes were tested. The node numbers in these meshes were 200×100×60 (Mesh 1), 300×150×90 (Mesh 2) and 400×200×120 (Mesh 3). The mesh independence results have been shown in Fig. 2.

Once validated, the work was extended to the case of a compound channel. The dimensions of the compound channel were as follows. It had a main channel width of 0.5m, floodplains on both sides had width of 0.35m each and water depth was 0.16m. The vegetation height was 25mm. The boundary conditions used in this work were as follows.

At the inlet, the uniform velocity was assumed. At the outlet, the pressure outlet boundary condition was employed. The free surface was treated as symmetry boundary condition. It means that the velocity profiles will be normal to the free surface and there gradient will be zero. The side walls were assumed as no slip (wall) boundary conditions. The sidewalls were assumed to be smooth surfaces. The drag force was not introduced into the model and instead a no slip boundary condition was imposed on the periphery of the circular elements. This is because the water particles in touch with the vegetation elements have zero velocity and zero slip boundary condition is the true representation of this situation. That's why this boundary condition has been used in the simulation work.

The standard wall function was used as a near wall treatment. It was ensured that the y+ distance was such that the first cell lied with in fully turbulent region and log-law exists in that part of the flow. As we are using standard wall function, so in the near wall viscous region there is no need of turbulence model. Instead this wall function will take care of it. The turbulence model will act on the region outside this viscous zone. That's why first node should be outside this viscous region and in the fully turbulent region where turbulence model will be imposed. The convergence was assumed to be attained when all the residuals reached a value of $1\times10^{-6}$. The default values of under-relaxation factors along with SIMPLE algorithm were employed for pressure-velocity coupling. The first-order upwind scheme has been incorporated for continuity, momentum, turbulence kinetic energy and its dissipation rate.

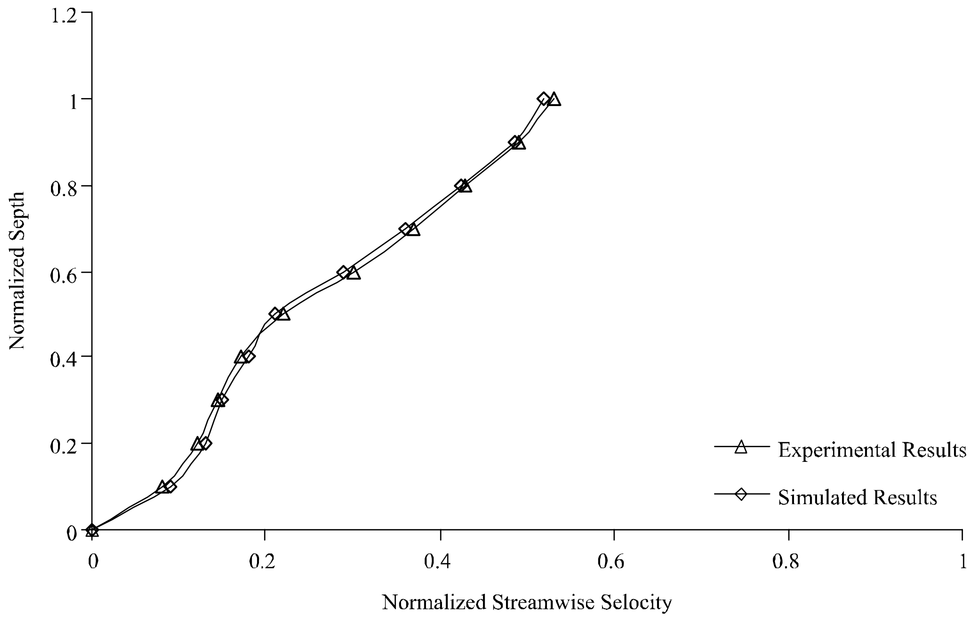


*FIG. 1. COMPARISON OF EXPERIMENTAL DATA WITH SIMULATED RESULTS*

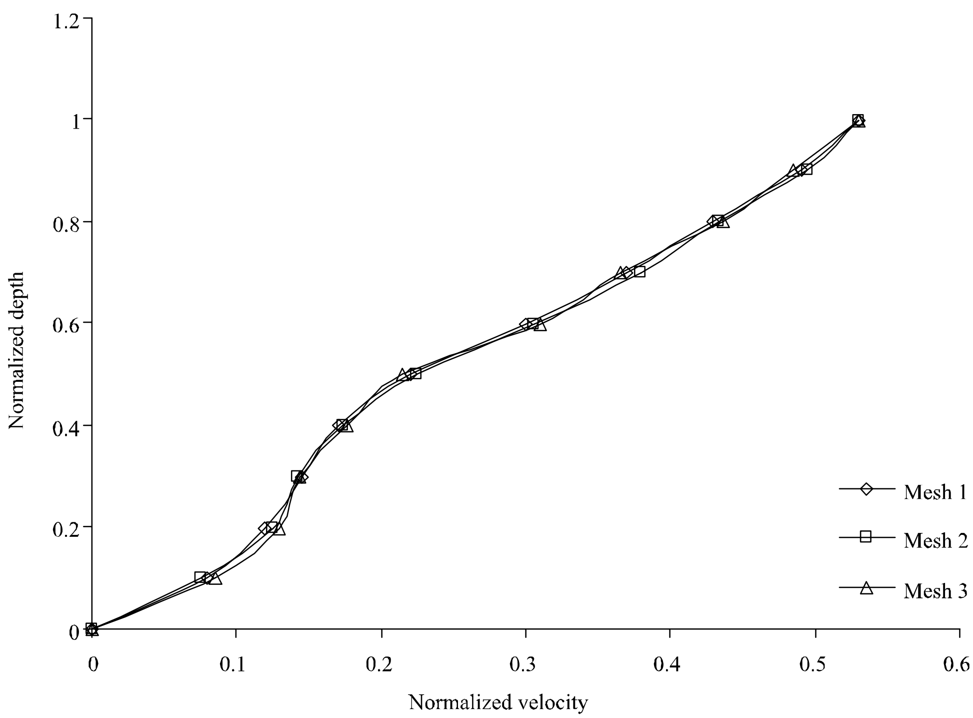


*FIG. 2. MESH INDEPENDENCE RESULTS*

## 3. RESULTS AND DISCUSSIONS:

Different vegetation density values considered in this research work are 0.5, 1.0, 2 and $4m^{-2}$. These have been termed as density 1, 2, 3 and 4 respectively. The results for main velocity profiles, Reynolds stresses, bed shear stresses and side wall shear stresses for these densities have been shown in the Figs. 3-6 respectively. In this simulation work the x, y and z axes represent longitudinal, vertical and lateral directions respectively.

The Fig. 3 above shows stream-wise longitudinal velocity distributions for four different densities of the vegetation. It clearly indicates that the velocity is much less in the lower regions of the depth where there is vegetation, however it then grows steeply just above the vegetation and follows the log-law velocity profile throughout the depth. There is velocity dip near the free surface in all the four density cases which might be attributed to the presence of air-water interlink in that region. It has been observed that the increase in density results in a decrease in velocity in all the four cases. All the four cases followed the law of the wall.

The Fig. 4 indicates the distribution of Reynolds stresses in the channel for different density values. It has been seen that increasing density results in considerable drop in the peek value of Reynolds stresses which happen close to the bed i.e. at a height of around 0.025m. The drop in maximum value of Reynolds stress is approximately around 22% when density changes from minimum to maximum value. However, this impact on Reynolds stress keep on reducing as we move towards the free surface and it almost disappears some distance below the free surface. This diagram shows that Reynolds stresses which contributes towards the momentum transfer are influenced by the presence of vegetation and change in vegetation density also disturbs their magnitude.

The distribution of bed shear stresses over the width of the section of the floodplain has been shown in Fig. 5 for different vegetation density values. It has been observed that for all the vegetation cases, the boundary shear stresses are small close to the wall of the floodplain and then they increase sharply at a distance of around 0.1m. From there onward the bed shear stress values fluctuate ranging from 0.3-0.38 $N/m^2$. As the vegetation density was increased gradually to cases 2, 3 and 4, then it was noticed that the shear stresses decrease gradually. The variation between maximum and minimum is around 15%.

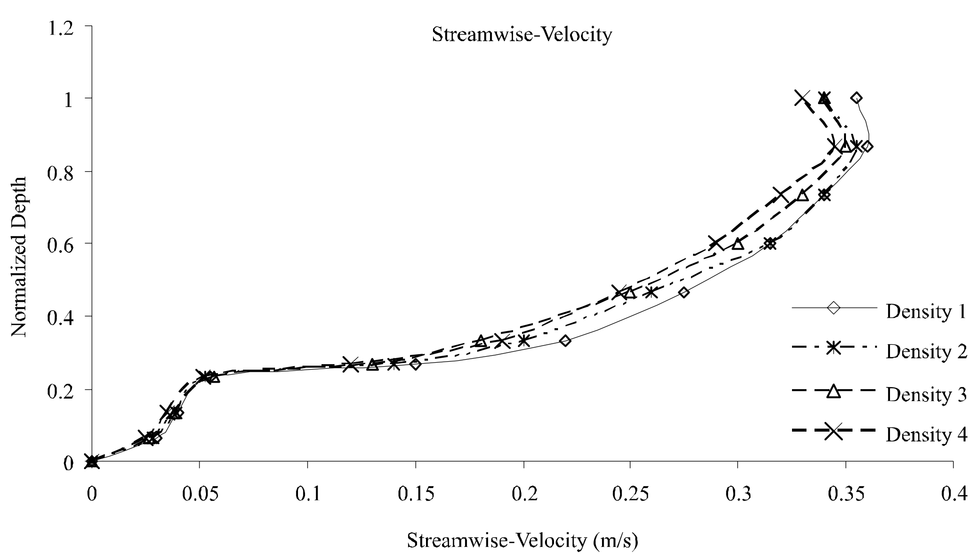


*FIG. 3. STREAM-WISE VELOCITY PROFILES OVER THE DEPTH OF THE FLOODPLAIN*

The Fig. 6 shows distribution of side wall shear stresses over the depth of the floodplain. Again it is clear from the diagram that the presence of vegetation has influenced the side wall shear stresses throughout the depth of the flow. At some regions such as close to the bed it is not so much prominent whereas in the rest parts it has more influence.

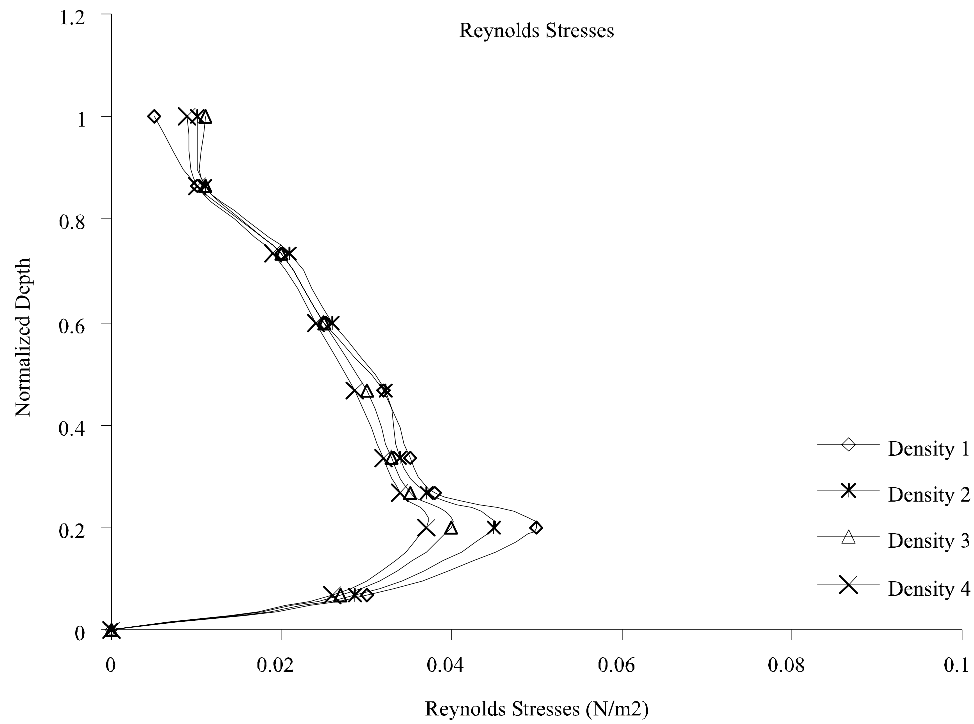


*FIG. 4. REYNOLDS STRESS DISTRIBUTION OVER THE DEPTH OF THE FLOODPLAIN*

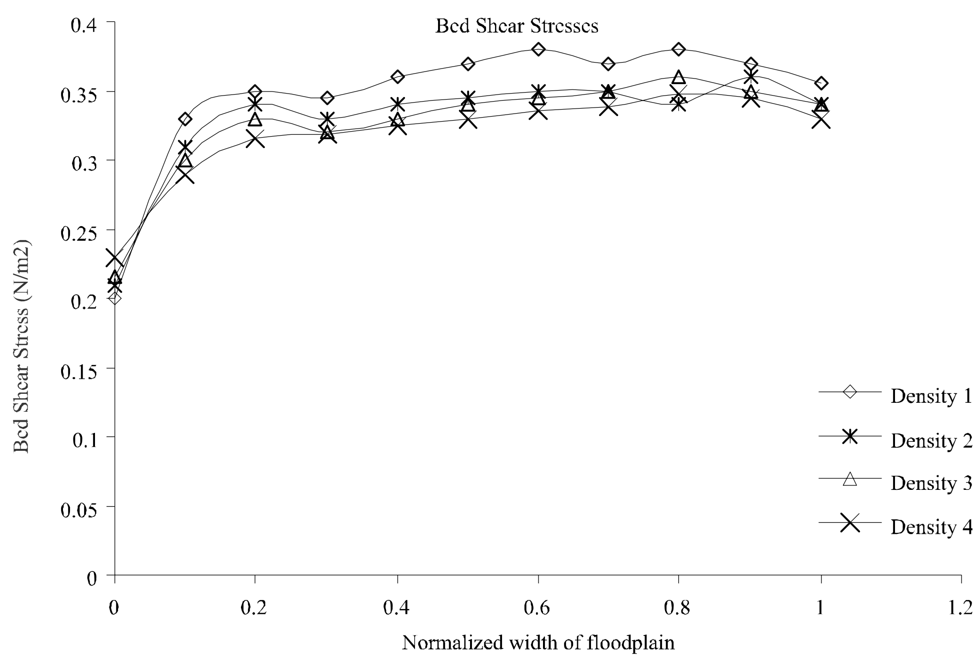


*FIG. 5. BED WALL SHEAR STRESSES OVER THE WIDTH OF THE FLOODPLAIN*

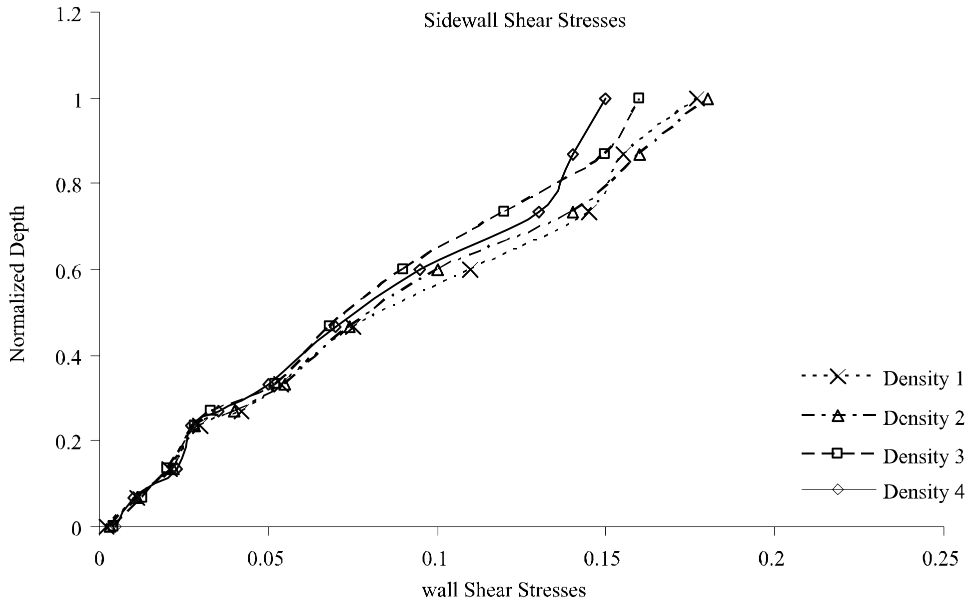


*FIG. 6. SIDE WALL SHEAR STRESSES OF FLOODPLAIN*

## 4. CONCLUSIONS

A numerical modeling has been done for investigating the impact of vegetation density on various flow characteristics of a compound channel. It was noticed that the presence of vegetation considerably impacts all important flow features such as primary velocities, Reynolds stresses, bed and wall shear stresses. By increasing the density, the velocity values were reduced considerably. The other three variables were also changed due to increase in density values. It is expected that this insight into the flow features will help in enhancing the understanding and improving the formulae of flow calculations.

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