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Simulation of bank protective effect of black alder root system (*Alnus glutinosa* (L.) GAERTNER) according to RipRoot Model

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Abstract: The paper deals with the significance of black alder (*Alnus glutinosa* (L.) GAERTNER) in connection with its bank protective function on torrent Hučava in geomorphological unit Poľana. Main goal was through simulation to show development of additional cohesion (c_r) and factor of stability (F_s) on 22 experimental profiles (EP) with vegetational bank protection taking account its density, age and root reinforcement. Data were calculated according to RipRoot model (POLLEN-BANKHEAD & SIMON 2009) and BSTEM (SIMON et al. 2009). We analyze potential development c_r (kPa) and F_s of black alder trees with using RipRoot model (Root Reinforcement Model) which was developed on this purposes in USA. According to simulation we found that the greatest additional cohesion (kPa) has black alder in range age from 30 to 60 years in dependency on number of stems per unit area (for example for 100% coverage at range age 30 - 60 years is additional cohesion in range from 14.34 to 14.78 kPa and 50% coverage in range from 7.17 to 7.84 kPa). Reduction of coverage percentage significantly decreases the value of the additional cohesion for example from value cr = 14.34 kPa for the 100% coverage, to value cr = 4.67 kPa for the 5% coverage 30 year old black alder. Simulated results show that different density of vegetation on the banks may to change the degree of stability of bank in the range of 3 degrees, from unstable, over conditional stable, to stable. Through the interventions into number of trees per unit area we can change the stability of the bank. We also found that for the further development of c_r and F_s is very important age of trees and soil type. Dependence $F_s = f(c_r)$ were statistically tested.

Keywords: black alder, riparian vegetation, bank stability, additional cohesion, RipRoot Model

Introduction

The riparian vegetation is significant from several reasons, but mainly of view of soil protection function and reinforcing the banks of water flows through its roots system. WYNN (2004), WYNN & MOSTAGHIMI (2006) indicate that riparian vegetation increase the stability of the banks and is very significant element of natural protection on the banks of water flows. In connection with presence or absence of riparian vegetation are processes of erosion significantly limited (reduced or increased). GREŠKOVÁ & LEHOTSKÝ (2007) suggest that riparian stands reinforce through their root system the banks of water flows and protect the banks against the erosion and negative effects of streaming water. VALTÝNI (1981) defines soil protection function of riparian vegetation as a reinforcement of the banks by root systems, also as inhibition of soil-erosion and of disturbances on the banks of water flows and reservoirs. NOVÁK et al. (1986) analyze influence of trees on the banks of water flows in connection with their location on the banks and their bank protection function. VALTÝNI (1974), ŠLEZINGR & ÚRADNÍČEK (2009) deal with using of several species of trees in various ecological conditions. The importance of riparian vegetation with accent on soil protection function confirm SIMON et al. (2009). These authors suggest that the soil loss of stream banks can be up 90% of total cubature of eroded material in the watershed per year. ROSGEN (2002) suggests that in some cases the soil-loss caused by erosion of the banks of water flows can be up 80% of total eroded material in watershed per year. POLLEN et al. (2004) provide that this share can be more than 50% of total eroded material in watershed per year. SIMON et al. (2011) confirm that by erosion of the banks is damaged averagely 52% of the banks of water flows. The influence of root systems of riparian stands of water flows on banks stability and their soil protection function analyze ABERNETHY & RUTHERFURD (2000), MICHELI & KIRCHNER (2002), SIMON & COLLISON (2002), EASSON & YARBROUGH (2002), POLLEN et al. (2004), etc. These authors confirm positive influence of the roots system on banks stability and indicate that the stability of the bank is in correlation with indicators of density of vegetation (number of stems per unit area) and growing biomass per unit area.

Black alder (*Alnus glutinosa* (L.) Gaertn.) is naturally widespread across all of Europe, from mid-Scandinavia to the Mediterranean countries, including northern Morocco and Algeria (KAJBA & GRACAN 2003). It is typically a component of mixed broadleaved forest and represents less than 1 per cent of the forest cover in most countries (TUROK et al. 1996) because most of the suitable sites have been converted to agriculture (NOIRFALISE 1984, BUGALA 2012). Also, former silvicultural practices favoured oak and ash over alder. However, in North Central Europe and South Central Europe, black alder represents approximately 5 percent of the forest area and forms large highly productive stands (ROISIN & THILL 1972, TUROK et al., 1996). Currently representation black alder in forests of Slovakia is about 0.75% which is 14473.42 ha (TU Zvolen, 2010). LUKÁČIK & BUGALA (2009) mention that the typical vertical extension of black alder in Slovakia is to 700 - 750 m a.s.l., somewhere also higher and grows in optimal condition up height of 30 – 35 m. Growth rates of black alder up to ages 7-10 are very fast but then slow rapidly. Sixty to seventy years is the maximum rotation period for growing timber. Black alder is a scattered, widespread and short-lived species that thrives in low-lying damp and riparian places. It is unusual European trees in that they fix nitrogen (ČERMÁK & FÉR 2007). It is typically tree of riparian stands on the banks of water flows. It has a use in flood control, stabilization of riverbanks and in functioning of the river ecosystems. The authors (CLAESSENS et al. 2010) investigated the root system black alder which is characterised by a huge set of 14 strong horizontal roots uniformly distributed with strong root buttresses, at the end arching into the depth, completed by some more roots of diameter 3–5 cm, growing mostly vertically into the depth of soil profile and filling very densely the central part of horizontal skeletal roots. Total rooting depth of soil profile is up to 2.0 m and rooting diameter under the stem axis is up to 6.0 m. It belongs to the trees species with short roots (max. 3 m), penetrating into medium depths (max. 1 m). YAU (2012) researched that the tree root zone is generally a space with a depth of between 1.5 m to 2 m and may extend laterally to a distance some three times the tree-canopy drip-line or tree height. GASSON & CUTLER (1990) found that 81% of all tree roots examined were less than 1.5 m deep, and up to 95% of all tree roots were less than 2 m deep. The research showed that no trees had roots deeper than 3 m and only 5% had rooting depths greater than 2 m. CROW (2005) indicates that different soil types and their properties are an important factor which influence depths and density of rooting the individual species of trees. There are cases where isolated roots have been found at depths much greater than (GILMAN 1990) is typically (90 - 99% of the roots occurs in depth of the upper 1 m of soil). The root system is adapted to very wet soils. Many strong, vertically growing, sinker roots anchor the tree on riverbanks, and they are able to penetrate deeply into wet and anaerobic soils (MAC VEAN 1956, SCHMIDT-VOGT 1971). KOSTLER (1968) observed roots reaching almost 5 m deep. Under anaerobic conditions, an oxygen supply for the roots comes from the aerial parts of the tree via enlarged lenticels on the stem (GILL 1975) connected to well-developed paerenchyma cells (LIEPE 1990). In the case of prolonged flooding, loss of function in the root system can induce the development of adventitious roots from lenticels (GILL 1975). NOVÁK et al. (1986) confirm that in our conditions the stands of black alder in our conditions are more resisting to damages and are able to resist without damages 15 to 20 day´s flooding in the vegetation period and 20–30 day´s flooding in time of quietness vegetation.

Material and methods

Experimental watershed Hučava is situated in geomorphological unit Poľana (Central Slovakia), subunits Detvianske predhorie and Vysoká Poľana. Torrent Hučava belongs to watershed of river Slatina and general watershed of river Hron. The main characteristics of experimental watershed and torrent Hučava are processed in Tab. 1.

Tab. 1. Characteristics of experimental torrent and watershed Hučava

Watershed area	41.16 km^2
Forest coverage of watershed	82.4%
Hydrologic number	4-23-03-070
Total lenght/ ø longitudinal gradient of torrent	14.285 km/5.33%
Average slope of the banks of watershed	32.3%
Average above sea level of the watershed	922 a.s.l.
Highest point of the watershed/lowest point of the watershed and waterflow	1458/523 a.s.l.
Absolute difference of altitude of torrent/of watershed	762/935 m
Highest point of waterflow	1285 a.s.l.
Average annual temperature of watershed	4.65^oC
Average annual precipitation in the watershed	937 mm
Average annual evaporation in the watershed	409 mm
Coefficient of torrent activity of the watershed	0.330

On 22 experimental profiles (EP) and experimental sections (ES) on the left and right side (total on the 44 experimental banks – EB) was simulated development of additional cohesion (c_r) of black alder and factor of stability (F_s) of banks. Verification of this simulation was performed on the basis of measurements in terrain on ES, EP and EB (JAKUBISOVÁ & JAKUBIS 2012). Modeling of bank protective effect of black alder root system was implemented on 15 meters long ES. Simulation of development of additional cohesion (c_r) was evaluated through RipRoot model - Root Reinforcement Model (POLLEN-BANKHEAD & SIMON 2009) on presentable EB (see Fig. 1 – Fig. 2). Simulation of development of F_s was realized according to BSTEM - 5.4 - ARS Bank stability and Toe Erosion Model (SIMON et al. 2009). This model was analyzed in the separate work (JAKUBISOVÁ 2011).

Characteristics of RipRoot model (Root-Reinforcement model)

RipRoot (POLLEN & SIMON 2005) is a global load-sharing fiber-bundle model. It explicitly simulates both the snapping of roots and the slipping of roots through the soil matrix, by determining the minimum applied load required to either break each root or pull each root out of the soil matrix. As the strength of each root is removed from the fiber bundle, the load is redistributed to the remaining roots according to the ratio of the diameter of each root to the sum of the diameters of all the intact roots. RipRoot builds on earlier work by WALDRON (1977), WU et al. (1979) and WALDRON & DAKESSIAN (1981).

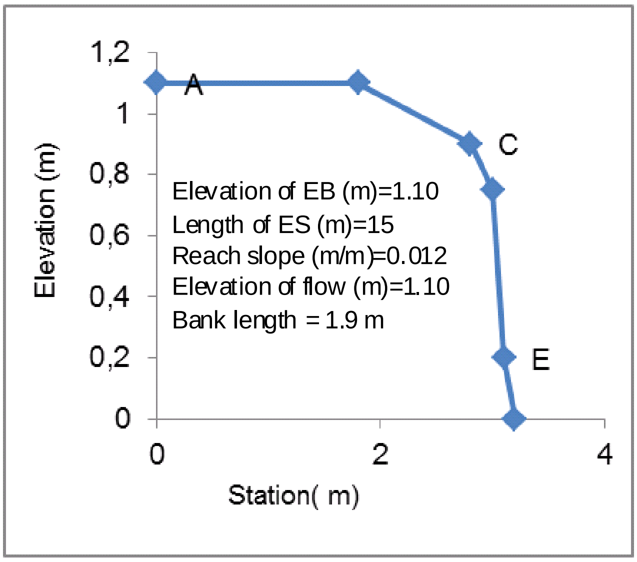

Fig. 1. Presentable EP.

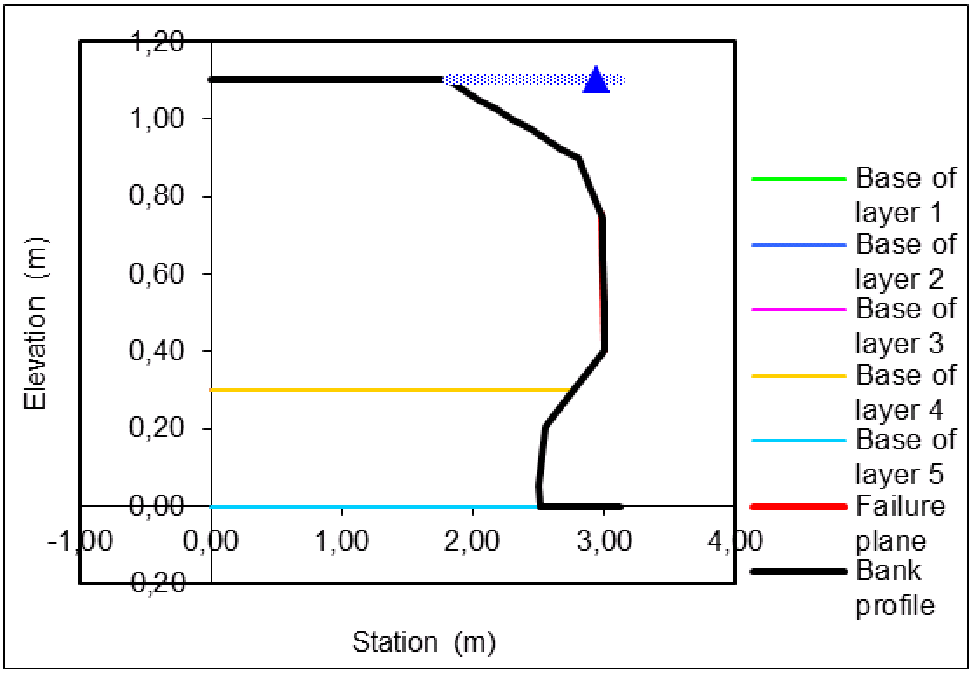

Fig. 2. Potential damaged toe of EP without bank protection (F_s = 0.84, unstable bank).

Theory of mechanical effects of vegetation on bank stability

Soil is generally strong in compression, but weak in tension. The fibrous roots of trees and herbaceous species are strong in tension but weak in compression. Root-permeated soil, therefore, makes up a composite material that has enhanced strength (THORNE 1990). Numerous authors have quantified this enhancement using a mixture of field and laboratory experiments. ENDO & TSURUTA (1969) used in situ shear boxes to measure the strength difference between soil and soil with roots. GRAY & LEISER (1982) and WU (1984) used laboratory-grown plants and quantified root strength in large shear boxes. WU et al. (1979), after WALDRON (1977) developed a widely-used equation that estimates the increase in soil strength (c_r) as a function of root tensile strength, areal density and root distortion during shear:

$$c_r = \frac{1}{A}\sum_{n=1}^{n=N}(A_r T_r)_n\left[\sin(90-\zeta)+\cos(90-\zeta)\tan\phi'\right] \qquad (1)$$

where c_r = cohesion due to roots (kPa); T_r = tensile strength of roots (kPa); A_r = area of roots in the plane of the shear surface; A = area of the shear surface; ϕ' = friction angle of soil (degrees); N = total number of roots crossing the shear plane; subscript n = n^{th} root; ζ - the variable (equation 2) where

$$\zeta = \tan^{-1}\left(\frac{1}{\tan\theta+\cot\chi}\right) \qquad (2)$$

where θ = angle of shear distortion (degrees); and χ = initial orientation angle of fiber relative to the failure plane (degrees).

POLLEN et al. (2004) and Pollen & Simon (2005) found that models based on equation 1 tend to overestimate root reinforcement because it is assumed that the full tensile strength of each root is mobilized during soil shearing and that the roots all break simultaneously. This overestimation was largely corrected by POLLEN & SIMON (2005) by developing a fiber-bundle model (RipRoot) to account for progressive breaking during mass failure. Validation of RipRoot versus the perpendicular model of WU et al. (1979) was carried out by comparing results of root-permeated and non-root-permeated direct-shear tests. These tests revealed that accuracy was improved by an order of magnitude by using RipRoot estimates, but some error still existed (POLLEN & SIMON 2005).

Methodology to determining of vegetational coverage on banks of water flows

We have created the methodology of vegetation density indicator (number of stems per unit area) on banks of water flows by the results of authors GASSON & CUTLER (1990), CROW (2005), ČERMÁK & FÉR (2007), CLAESSENS et al. (2010). In methodology we take account the crown projection area which is given by radius of circular base. The crown projection area of trees was used for the calculation of the coverage percentage of black alder on the EB. Throught this methodology was derived the effective area of bank protection taking account on the root reinforcement and age of trees. According to authors CLAESSENS et al. (2010) we derived also the effective depth of roots in dependency on the age of black alder. Density of coverage is determined by the number of stems per unit area.

The simulation the mechanical effects of vegetation on the bank stability using RipRoot model

Main goal was through simulation to show the development of additional cohesion and factor of stability on the EB through black alder stands taking account of its density, age and root reinforcement according to RipRoot model (POLLEN-BANKHEAD & SIMON 2009) and BSTEM (SIMON et al. 2009).

In terrain on straight ES of torrent Hučava was established presentable experimental section, the area with dimensions L (lenght of EB 15 m) and Y (distance from top to toe of EB). By the leveling method were determined geometric characteristics of EP: B (m) – width of cross section inside the banks, width of bottom b (m), depth of flow profile H (m) and values of longitudinal gradients i (%) of the ES. These data was used for the calculation in BSTEM. Subsequently was evaluated the potential development of bank roots reinforcement through additional cohesion (c_r) in dependency on age, vegetation coverage percentage and depth of black alder roots. In calculation of additional cohesion were taken into account soil conditions. Output data of simulation (Fig. 3, Fig. 4) were determined through BSTEM (SIMON et al. 2009) and RipRoot model (POLLEN-BANKHEAD & SIMON 2009). In terrain were evaluated numbers of black alder on EB and were plotted into situation in scale 1:100. Subsequently was plotted and determined coverage of black alder through methodology to determining of vegetational coverage on banks of water flows.

Effect of root systems to stability of the banks of water flow was calculated as the additional cohesion – c_r (kPa). This methodology of computation takes account the age, depth of roots and percent coverage vegetation (black alder and wet meadow). In view of conditions we take account hydrophilic herbaceous undergrowth (wet meadow). According to BSTEM was calculated factor of stability (F_s). Computed results were compared with measured in terrain. The Factor of stability - F_s (dimensionless number) according to BSTEM is evaluated in three levels: if $F_s > 1.3$ – the bank is stable, if F_s is from 1.0 to 1.3 – the bank is conditionally stable, if $F_s < 1.0$ – the bank is unstable.

Results and Discussion

Input data into model about hydraulic conditions were identified in the terrain on EP (Fig. 1 - 3). We present the results of simulation between variables on EB and EP: dependence between depth of the roots - H_k (m), age (years) and additional cohesion according to percentage black alder coverage – c_r (kPa) (Fig. 4 and Fig. 5) and between additional cohesion - c_r (kPa) and factor of stability - F_s (Fig. 6). We found through simulation that the greatest additional cohesion (kPa) has black alder in range age from 30 to 60 years in dependency on the number of stems per unit area. For example for 100% coverage in range of age

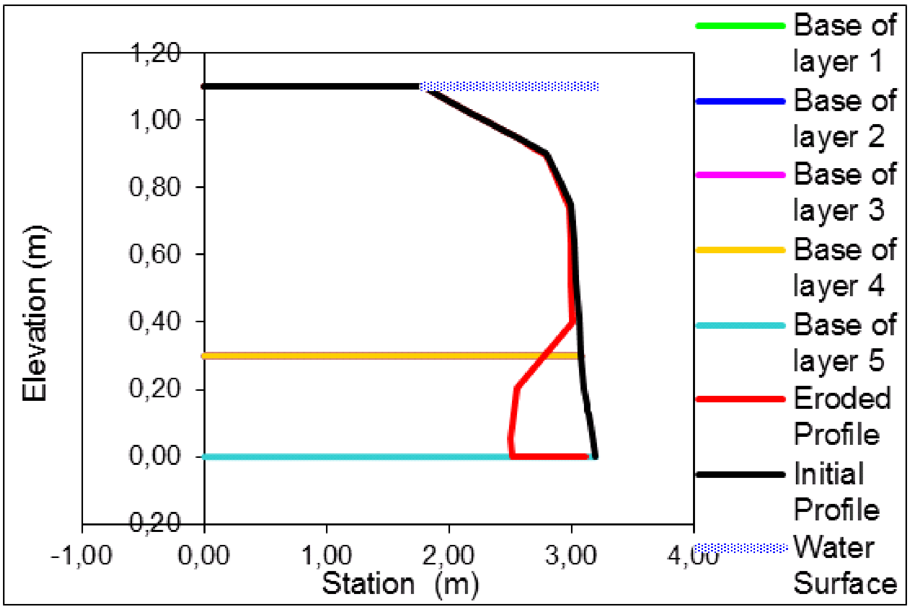

Fig. 3. Potential eroded EP after simulation without bank protection.

30 - 60 year is the additional cohesion in range from 14.34 to 14.78 kPa and 50% coverage in range from 7.17 to 7.84 kPa (Tab. 2). The c_r in range of age from 30 to 60 years is not significantly changed. Reduction of the coverage percentage decreases significantly the value of the additional cohesion and vice versa. For example from value c_r = 14.34 kPa (for the 100% coverage) to value c_r = 4.67 kPa (for the 5% coverage) what represents values F_s = 1.57 (stable bank) and F_s = 1.08 (conditional stable bank) for the 30 year old of black alder. Simulated results show (Tab. 2) that through different density of vegetation we may to change the degree of stability of the bank in the range of 3 degrees, from unstable, over conditional stable, to stable. Through the interventions into number of trees per unit area we can change stability of the bank. We also found that the age of trees and soil type (JAKUBISOVÁ 2011) is very important for the further development of additional cohesion and factor of stability. MICHELI, KIRCHNER (2002) also confirmed that stability is correlated with indicators of vegetation density, consisting of the number of stems per unit area.

Dependance F_s = f (c_r) was statistically tested (Fig. 6 and Tab. 3) for 44 EB on 22 EP. The results indicated close correlation between the additional cohesion of black alder and factor of stabilty F_s (correlation coefficient R = 0.993 and coefficient of determination R^2 = 0.986). The calculated results c_r and F_s are in accordance with existing stability of EB confirmed in terrain. The analysis confirms the important influence of black alder to stability of the banks of water flows.

Tab. 2. Simulation of black alder (BA) vegetational coverage, additional cohesion and factor of stability

			Vegetational coverage of BA/MW+ (%)										
			100/0	90/10	80/20	70/30	60/40	50/50	40/60	30/70	20/80	10/90	5/95
No	Age	H_K (m)	Additional cohesion / Factor of stability c_r (kPa) / F_s (dimensionless number)										
1	5	0,26	1.77/0.91	1.75/0.91	1.75/0.91	1.73/0.90	0.72/0.87	0.72/0.87	0.72/0.87	0.30/0.85	0.25/0.85	0.11/0.84	0.05/0.84
2	10	0.40	5.90/1.14	5.17/1.10	4.09/1.04	3.40/1.01	3.35/1.01	3.30/1.01	2.95/0.99	2.95/0.99	2.33/0.96	2.21/0.95	2.20/0.95
3	15	0.50	8.81/1.29	8.56/1.28	7.80/1.24	6.12/1.15	5.90/1.14	5.17/1.10	4.80/1.08	4.67/1.08	4.68/1.08	4.57/1.07	4.51/1.07
4	20	0.58	11.65/1.43	10.63/1.38	9.50/1.32	8.72/1.28	6.97/1.19	5.95/1.14	5.36/1.11	5.12/1.10	5.00/1.09	4.73/1.08	4.61/1.08
5	25	0.64	13.42/1.52	11.77/1.44	10.46/1.38	9.03/1.30	8.52/1.27	6.84/1.19	5.89/1.14	5.38/1.12	5.11/1.10	4.8/1.09	4.67/1.08
6	30	0.69	14.34/1.57	12.71/1.49	11.55/1.43	9.95/1.35	8.81/1.29	7.17/1.21	6.02/1.14	5.49/1.12	5.22/1.10	4.8/1.09	4.67/1.08
7	35	0.73	14.65/1.58	13.62/1.53	11.63/1.43	10.59/1.38	8.83/1.29	7.83/1.24	6.04/1.14	5.63/1.13	5.26/1.11	4.89/1.09	4.71/1.08
8	40	0.77	14.73/1.59	13.7/1.54	11.94/1.45	10.63/1.38	8.89/1.30	7.83/1.24	6.11/1.15	5.63/1.13	5.26/1.11	4.89/1.09	4.71/1.08
9	45	0.81	14.77/1.59	13.74/1.56	11.99/1.50	10.94/1.40	8.91/1.32	7.84/1.26	6.12/1.16	5.67/1.14	5.26/1.11	4.89/1.09	4.71/1.08
10	50	0.84	14.78/1.60	13.74/1.56	11.99/1.50	10.94/1.40	8.92/1.32	7.84/1.26	6.12/1.16	5.67/1.14	5.26/1.11	4.89/1.09	4.71/1.08
11	55	0.87	14.78/1.60	13.74/1.56	12.00/1.50	10.94/1.40	8.93/1.32	7.84/1.26	6.15/1.17	5.67/1.14	5.26/1.11	4.89/1.09	4.71/1.08
12	60	0.90	14.78/1.60	13.74/1.56	12.00/1.50	10.94/1.40	8.93/1.32	7.84/1.26	6.15/1.17	5.67/1.14	5.26/1.11	4.89/1.09	4.71/1.08

Explanatory notes: Age – age of BA; H_k – depth of roots of BA (m); (100 – 5) - indicators of BA density (number of stems per unit area in %); 0 – 95 - indicators of Meadow Wet density (MW^+); c_r - additional cohesion by the RipRoot (kPa); F_s – factor of stability by the BSTEM (dimensionless number)

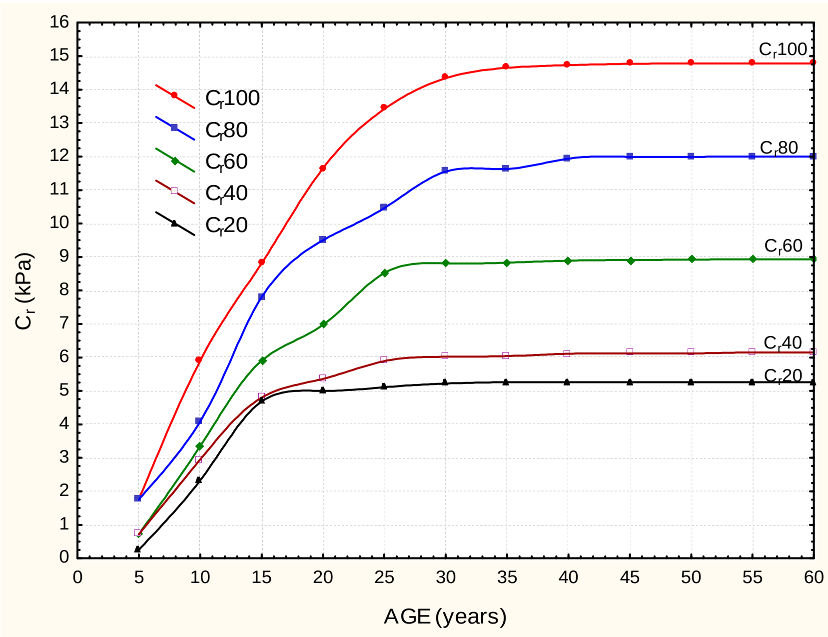

Fig. 4. Dependence: c_r = f (Age of black alder) on EP

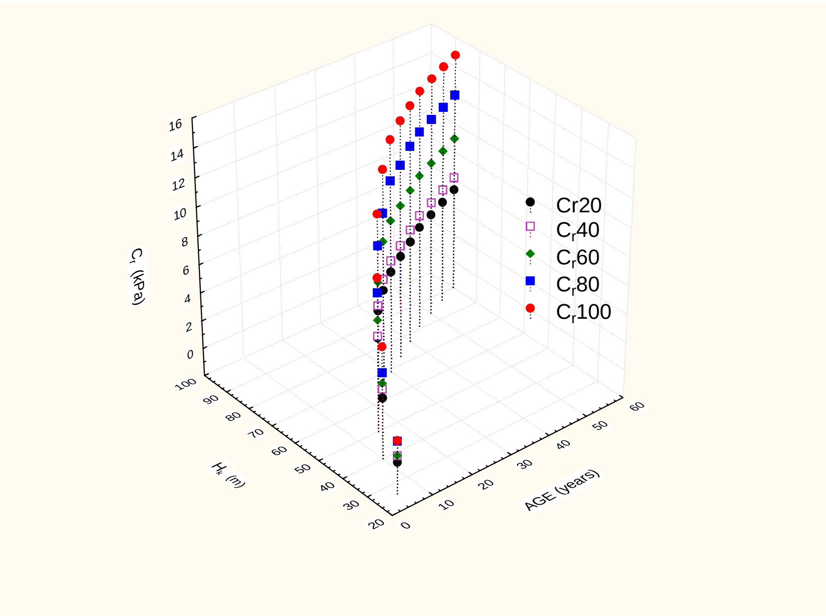

Fig. 5. Dependence between variables: c_r (kPa), H_k (m), Age of black alder (years)

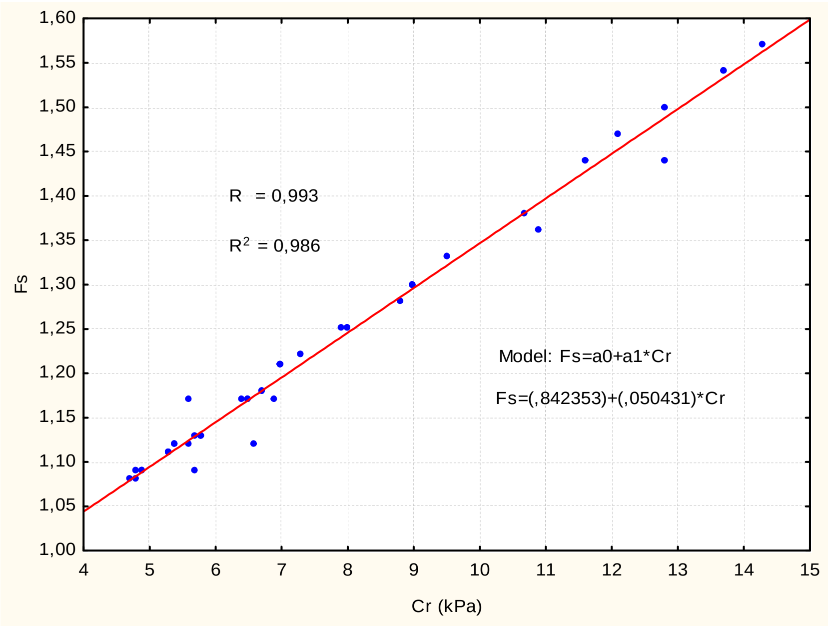

Fig. 6 Dependence: $F_s = f(c_r)$

Tab. 3. Statistical testing by ANOVA

Model: $F_s = a_0 + a_1 * c_r$ Dependent Variable: F_s					
Effect	Sum of Squares	Degrees of Freedom	Mean Squares	F - value	p - value
Regression	67.65213	2	33.82607	114881.9	0.00
Residual	0.01237	42	0.00029		
Total	67.66450	44			

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