

# Investigation of Mechanical Properties and Flow Resistance of Flexible Riverbank Vegetation

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## Abstract

Flexibility of plants in the inter embankment zone makes them bend, to various degrees, under the force of flowing water. Determination of the mechanical properties is crucial for forecasting the behavior of vegetation and determining the hydrodynamic drag forces resulting from vegetation. This is also directly linked to the water table in the channel. Laboratory measurements were carried out for branches of willow, reed and alder, allowing for the determination of modulus elasticity, modulus of non-dilatational strain, limit of elasticity for the twigs, and their humidity. Mechanical properties of samples under investigation mainly depended on the humidity and species of plants. Experimental results confirmed considerable variability of parameters even within samples coming from a single plant.

**Keywords:** shrubs, modulus of elasticity, vegetation stiffness, flow resistance

## Introduction

Vegetation is one of the most important biological components of rivers and relative floodplains. It is composed of a mixture of species (herbaceous, woody species – shrubs, trees) which have different relations to the submerged channel. Aquatic herbaceous species are inside the channel (submerged flexible vegetation), while grasses, shrubs (flexible roughness) and trees (rigid roughness) are usually within the river margins and wetlands (non-submerged vegetation) [1]. The presence of riparian and aquatic vegetation is crucial for maintaining ecosystem functions, for other biota, and for controlling the erosion of the river bed, sustaining the riverbanks, and trapping sediments [2, 3]. On the other hand, if the river system is unbalanced, the vegetation can increase extensively, which from the standpoint of flood protection has a negative impact.

The vegetation encroachment decreases channel flow capacity, and can locally raise the water level and increase flooding [4]. Clearly this is not desirable. In many cases cutting down the trees, shrubs and reeds in floodplains is not necessary and can be avoided. Throughout the decades, hydrotechnical work related to river training often contributes to the destruction of ecosystems. In many cases human interference with the environment has irreversible effects. To prevent this and to protect the riparian vegetation, reliable analyses and calculations of the impact of vegetable clusters on flood flows are required. Also, understanding the structure of the vegetation and determining its parameters are a prerequisite for a reliable mathematical model of the flow [5, 6].

Flow resistance problems are usually classified in two groups [7]: flow over submerged, short vegetation and flow through non-submerged tall vegetation. Most authors that study vegetation resistance have concentrated on submerged flexible vegetation and rigid roughness [8, 9]. The

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present work, however, is confined to the selected species of non-submerged vegetation: reeds, willow, and alder (flexible roughness), and aims to contribute to forecasting its effects on river flows.

Apart from hydrodynamic parameters, the influence of vegetation on flow conditions greatly depends on the plant's species, the plant's development phase, and its geometric and mechanical properties [10, 11]. Among other mechanical properties, a key role is played by the flexibility (elasticity) of the plants. This parameter makes the plants bend to various degrees under the force of the flowing water. It is precisely this parameter, the modulus of elasticity, that determines the force required for bending. Its determination is crucial for forecasting the behavior of the vegetation and defining the hydrodynamic drag forces resulting from the vegetation [7, 9, 12]. Less is known about the basic mechanical properties – including elasticity of flexible roughness and its effects on river flows. There is little field data available, other than overall roughness coefficients representing limited flow conditions [13-15]. Some field data of vegetation biomechanical properties has been published [9, 16, 17], but most of the laboratory studies were conducted using artificial roughness. However, in some recent investigations actual plants are used [18-20]. The objective of this study is to research the flexibility of select riparian species.

### Laboratory Research

In the framework of a joint research project by Poznań University of Life Sciences and Wrocław University of Environmental and Life Sciences, a laboratory investigation of physical and mechanical properties of selected species of flexible river valley vegetation was carried out. Measurements were performed for the following vegetative elements (twigs/branches): purple willow (*Salix purpurea* L.), common reed (*Phragmites communis* Trin.), and speckled alder (*Alnus rugosa* (Du Roi) Spreng.) [21]. These species are the most representative for broadly understood floodplains, where the influence of vegetation on flood flow conditions is considerable.

Whereas the investigation of the physical properties focused solely on plant humidity, the estimation of the mechanical properties included the following parameters: modulus of elasticity of vegetation, modulus of non-dilatational strain, limit of elasticity for the twigs being studied as well as determining the time dependence of strain. Measurements were carried out for vegetation that was both in its natural condition (humid) as well as for plants that had been naturally dried (after having been stored for approximately 2 months in a dry, well-aired place). Due to the specificity of the material under study and considering the fact that it mainly consisted of wood tissues, the analysis of a twigs' physical properties was done using the methods developed for wood assessment. Modifications of the methods described in standards [22, 23] were mainly due to the size and shape of samples. All these alternations were meant to make our research reliable.

Investigation of mechanical properties of vegetation was performed within the following measuring ranges:

1. Type and number of samples: 95 willow twigs in two series of 52 and 43 elements, respectively, 40 reed elements and 50 alder twigs.
2. Condition of plants under study: young willow (up to 2 m in height), young alder (up to 2 m in height), dry reed, fresh reed (summer).
3. Length: the length of all the samples under study was 0.5-1.0 m.
4. Diameter: the diameter range per plant species was as follows:
  - a) willow: outer diameter 6.40-9.55 mm
  - b) alder: outer diameter 8.20-9.60 mm
  - c) fresh reed: outer diameter 7.95-11.00 mm; inner diameter 6.75-9.80 mm
  - d) dry reed: outer diameter 6.20-9.70 mm; inner diameter 5.45-8.55 mm
5. Loads: before commencement of actual measurements load tests were performed on a substitute set of sample (with similar diameters). After the stress characteristics were obtained, it turned out that the optimal step for smaller samples is 10 g, while for bigger samples the step was set to be 25 g. Considering twig diameter, the following load ranges were assumed for each vegetation group individually:
  - a) willow: max load for samples with smaller and bigger diameters was 200 g and 500 g, respectively
  - b) alder: max load applied to a sample was 500 g regardless of the diameter
  - c) fresh reed: load was being applied to the sample until its destruction
  - d) dry reed: load was being applied to the sample until its destruction
6. Deflection: based on the performed tests, deflection ranges were assumed to be as follows:
  - a) willow: 0-350 mm
  - b) alder: 0-350 mm
  - c) fresh reed: 0-250 mm
  - d) dry reed: 0-150 mm

### Investigation of Plant Humidity

Vegetative substance is a porous and hygroscopic material. The relative plant humidity  $W_w$ , understood to be the plant water content mass to wet plant mass ratio, was determined based on eq. (1) recommended for wood assessment in standards [23]:

$$W_w = \frac{m_w - m_0}{m_w} \cdot 100\% \quad (1)$$

...where:  $m_0$  is the mass of wood when completely dry and  $m_w$  is the mass of wood when humid [kg].

Samples for humidity measurements were obtained by cutting the twigs used in the measurements of elasticity into pieces of approximately 5 cm in length. After marking, samples were weighed on scales of 0.0001 g accuracy ( $m_w$ ).

Table 1. Relative humidity for investigated vegetative samples.

$W_w$	Willow I		Willow II		Reed		Alder	
	Fresh	Dry	Fresh	Dry	Fresh	Dry	Fresh	Dry
	[%]							
$\bar{x}$	59.09	8.23	56.73	7.47	68.47	8.76	40.34	4.95
$\partial$	5.08	0.71	5.17	0.89	18.07	0.72	3.65	3.51
$\nu$	0.09	0.09	0.09	0.12	0.26	0.08	0.09	0.71
max.	69.52	9.45	67.39	9.46	87.47	9.96	46.90	18.38
min.	48.08	6.07	45.01	6.05	19.73	4.80	29.74	1.06

Next, they were left to dry naturally in a well-aired room. After 2 months samples were weighed again. The next stage was to place all the samples in a drier at  $105 \pm 2^\circ\text{C}$  until completely dry. The process was controlled by weight checks performed every two hours. After drying, samples were cooled off and weighed immediately ( $m_0$ ) to prevent them from absorbing humidity by more than 0.1%.

Eq. (1) was used to calculate the humidity of samples (both the fresh and the naturally dried ones). Results for willow (two series), reed, and alder were analyzed as random samples for which the mean value  $\bar{x}$ , standard deviation  $\partial$ , variation coefficient  $\nu$  (defined to be the standard deviation to the mean value ratio), and sample min and max value were calculated. A summary of results is given in Table 1.

### Investigation of the Modulus of Elasticity

The theory behind the modulus of elasticity for shrubs is discussed in detail in [9, 24]. From Hooke's Law, the stress to unit strain ratio is a constant material characteristic called the modulus of elasticity  $E$ . In arboriculture the modulus of elasticity is usually considered under static bending. In our laboratory measurements, to calculate the modulus of elasticity  $E$  we used eq. (2). The existence of two types of plant stem cross-section were taken into account: filled (e.g. willow, alder) and hollow (e.g. reed).

$$E = \frac{P \cdot l^3}{3 \cdot I_x \cdot w} \quad [\text{Pa}] \quad (2)$$

...where  $P$  – applied load [N],  $l$  – sample length (from the fixing point to the point at which load was applied) [m],  $I_x$  – moment of inertia for the cross-section of the vegetative element [ $\text{m}^4$ ], and  $w$  – deflection of sample [m].

The moment of inertia of cross-section  $I_x$  was calculated using the following equations:

- for filled stem cross-section of investigated samples (willow, alder):

$$I_x = \frac{\pi D^4}{64} \quad [\text{m}^4] \quad (3)$$

- for hollow stem cross-section of investigated samples (reed):

$$I_x = \frac{\pi}{64} \cdot (D_1^4 - D_2^4) \quad [\text{m}^4] \quad (4)$$

...where  $D$  – outer diameter of sample averaged over length [m],  $D_1$  – outer diameter of sample [m],  $D_2$  – inner diameter of sample [m].

In order to take measurements of the modulus of elasticity of vegetative twigs a special measurement set-up was built, shown in Fig. 1. The experiment consisted of taking the measurements of deflection  $w$  of rigidly fixed vegetative elements. Increasing loads were applied to twigs by hanging weights  $P$  at one end of the vegetative sample. As a rule, 5 measurements were taken. Weight was adjusted to stem rigidity so as to keep max deflection below 35 mm. Measurements of deflection were taken by means of a specially adjusted measurement needle with 0.1 mm accuracy. Measurements of force arm length  $l$  were performed with 1 mm accuracy and load was mea-

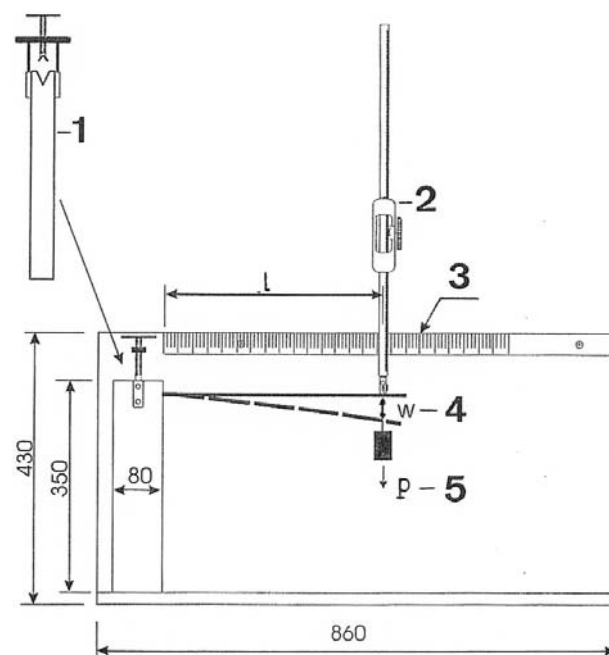


Fig. 1. Schematic diagram of the measurement set-up (1 – fixing for twig clamps, 2 – measurement needle, 3 – centimetres graduation, 4 – deflection, 5 – weight).

Table 2. Modulus of elasticity for investigated vegetative samples.

$E$	Willow I		Willow I		Reed	Alder	
	Fresh	Dry	Fresh	Dry	Fresh	Fresh	Dry
	[MPa]						
$\bar{x}$	4,077	7,380	4,476	8,882	3,328	2,523	3,762
$\partial$	2,122	3,179	1,355	1,634	4,356	852	976
$\nu$	0.52	0.43	0.30	0.18	1.31	0.34	0.26
max.	10,171	17,478	7,431	12,949	17,279	4,597	5,666
min.	918	2,568	720	6,913	269	680	1,906

sured to an accuracy of 0.01 g. Diameter  $D$  was measured using a slide caliper to an accuracy of 0.1 mm.

The modulus of elasticity calculated for each plant species based on eq. (2) was the average of results obtained for all the twigs. The value for each twig was an average taken over five measurements at different loads. Measurements were carried out both for dry and fresh twigs. A summary of results (processed) is given in Table 2.

#### Investigation of the Modulus of Non-Dilatational Strain

We developed a mathematical model that takes into consideration the shape, size, and variability of twig diameter over length and enables the calculation of the modulus of elasticity for vegetative elements being twisted. The modulus of non-dilatational strain  $G$  can be calculated from the following equation:

$$G = \frac{P \cdot r \cdot l}{\phi \cdot J_0} \cdot \frac{1}{3} \cdot \left(\frac{D}{d}\right)^2 \left(\frac{D}{d} + 1 + \frac{d}{D}\right) \quad [\text{Pa}] \quad (5)$$

...where the so-called polar moment of inertia is:

$$J_0 = \frac{\pi D^4}{32} \quad [\text{m}^4] \quad (6)$$

In eq. (5),  $\phi$  is the angle of twist for a twig with diameter  $d$  and  $D$  at its extremes, fixed between clamps. The distance between clamps is  $l$ . This angle (in radians) had to be determined experimentally. A schematic diagram of the measurement set-up is shown in Fig. 2. The lower section of the twig, placed on a rotating disc of radius  $r$ , was pulled with a twisting moment,  $M$ , resulting from the application of force  $P$  ( $M=Pr$ ).

The modulus of non-dilatational strain,  $G$ , is related to Young's modulus,  $E$ , and Poisson coefficient  $\nu$ . The relationship is as follows:

$$G = \frac{E}{2(1+\nu)} \quad [\text{Pa}] \quad (7)$$

thus, the modulus of elasticity of investigated twigs can be calculated from:

$$E = G \cdot 2(1+\nu) \quad [\text{Pa}] \quad (8)$$

The Poisson coefficient  $\nu$  for steel is 0.30 [-], but no confirmed data can be found in the literature for willow and alder twigs. Therefore, measurement results were not converted to the modulus of elasticity  $E$ . On the other hand, due to the fragility of stems,  $G$  could not be measured for reed. In series I, 14 willow twigs were studied with an average diameter of 1.13 cm, in series II – 17 twigs with an average diameter of 1.22 cm. For alder, we select-

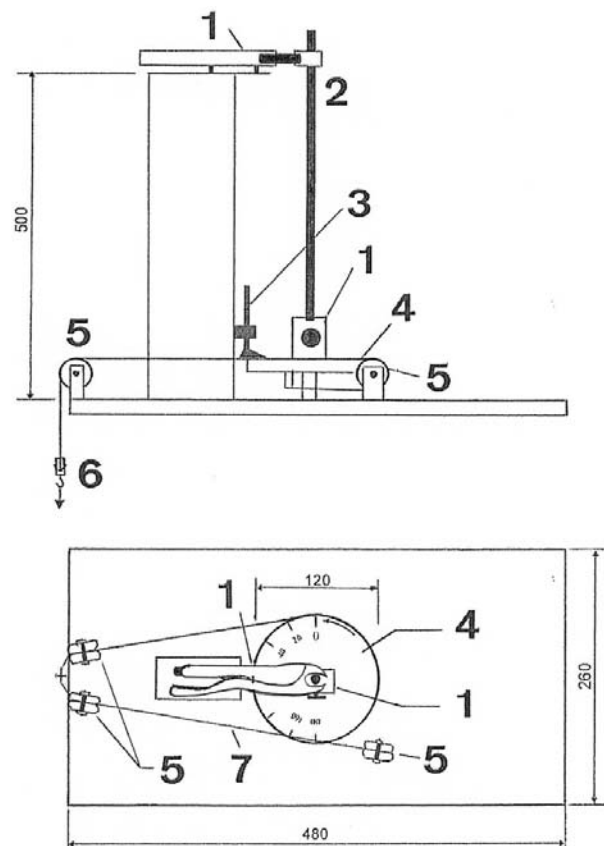


Fig. 2. Schematic diagram of the research stand for measuring the modulus of non-dilatational strain (1 – fixture for twig clamps, 2 – twig, 3 – indicator of protractor, 4 – rotating disc with protractor, 5 – block, 6 – weight, 7 – rope).

Table 3. Modulus of non-dilatational strain for investigated vegetative samples.

G	Willow I		Willow I		Alder	
	Fresh	Dry	Fresh	Dry	Fresh	Dry
	[MPa]					
$\bar{x}$	491.58	2,236.97	454.42	2,118.58	884.71	1,594.59
$\partial$	381.84	1,343.74	270.04	953.56	411.95	563.84
$\nu$	0.78	0.60	0.59	0.45	0.47	0.35
max.	1,423.48	4,551.99	1,128.92	3,579.57	2,011.22	2,839.35
min.	125.61	383.42	117.48	689.83	376.28	856.53

ed 17 twigs with an average diameter of 1.18 cm. Measurements were performed by twisting the twigs fixed in two clamps 44 cm apart. The twisting moment was created by turning a 12 cm (dia.) disc *via* a gear, a system of blocks and connectors that transmitted loads from scaled weights attached to a string.

The modulus of non-dilatational strain calculated for different plant species based on eq. (5) was an average over the sample of all twigs and the value for each twig was an average of three measurements taken at different loads (e.g. 806.4 g, 1,224.2 g, and 1,723.3 g). The protractor scale on the rotating dial allowed for reading the twist angle at a given load with 1° accuracy. By comparing the twist angle readings with the “0” position (90°) angle increments due to the twisting moment were obtained. Measured results for the non-dilatational strain for both fresh and dry twigs are presented in Table 3.

#### Investigation of the Limit of Elasticity for Vegetation

One of the ways to illustrate the elastic properties of plants under study (with known stem cross-sections) is to plot the measured absolute deflection increments  $w$  (X-axis) versus the loads  $P$  being applied (Y-axis), as shown in Fig. 3. For stress gradually increasing from zero, one obtains a straight-line section of the plot, which corresponds to the direct proportion between stress and deformation (deflection). This section corresponds to the range of applicability of Hooke's Law (Fig. 3). Introduction of forces (e.g. the hydrodynamic thrust of flowing water) in excess of the limit of proportionality translates to sharper increase of deflection (no straight line on the plot). Twigs, however, retain their elastic properties up to the so-called limit of elasticity, beyond which deflection becomes irreversible. For the inter-embankment vegetation the possibility that stems will eventually break should also be considered, as it translates directly to the hydraulic conditions in the river channel (flow drag, water level, etc.). Determined graphically, as in the sample (Fig. 3), the limits of vegetative elasticity  $P'$  (willow, alder, fresh and dry reed) for twig diameter  $d$  are given in Table 4.

Table 4. Limit of elasticity for investigated vegetative samples.

$P'$	Willow fresh	Reed fresh	Reed dry	Alder fresh
	[N]			
d [mm]	6-10	8-11	6-10	8-10
$\bar{x}$	2.71	0.74	2.37	3.39
$\partial$	1.27	0.46	0.96	0.65
$\nu$	0.47	0.63	0.41	0.19
max.	3.92	1.47	3.43	4.42
min.	1.28	0.29	0.98	2.70

#### Time Dependence of Plant Strain

To verify the influence of time of operation  $t$  on the size of strain  $w$ , measurements were carried out for selected samples of willow, alder, fresh reed, and dry reed. A 500 g weight was being applied for 5 minutes to each sample and plant deflection was measured in 1-minute intervals. A sample graph of the relationship  $w=f(t)$  by 500 g weight for the representative willow and alder twigs is shown in Fig. 4. However, due to the too short measurement time span, the obtained results cannot be regarded as sufficient for quantitative analysis.

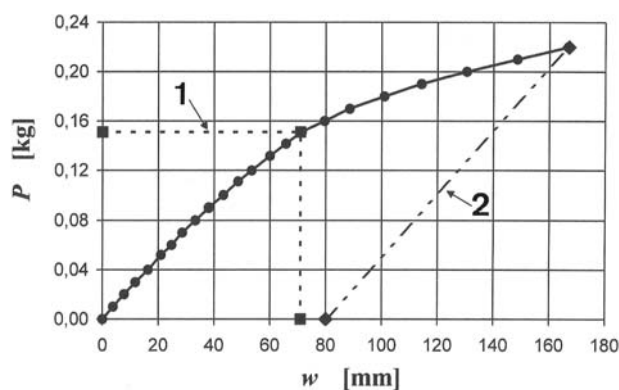


Fig. 3. Stress intensity for fresh reed branches (sample No. 4,  $d=11$  mm): 1 – limit of elasticity, 2 – elastic recovery.

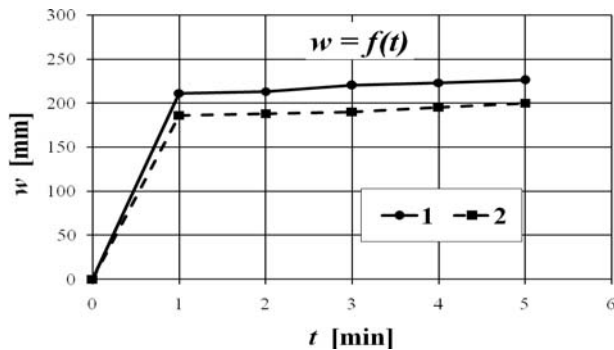


Fig. 4. Influence of time  $t$  on the size of strain  $w$  for investigated twigs (1 – alder, 2 – willow).

### Discussion of Results

Results of experiments carried out in relation to the investigation of basic mechanical properties of selected plants show that parameters are naturally prone to considerable changes, even within a sample taken from one plant specimen. This can be seen from the high span of the values of the variation coefficient  $v$ , which was used as a measure of homogeneity of a research sample.

Mechanical properties of investigated samples depend mainly on the plant species and humidity  $W_H$ . The later varied considerably. For example, the humidity of fresh willow samples was approximately 60% and plummeted to about 8% after drying. At the same time, the variation coefficient for dry plants was smaller than that for plants in natural condition.

Laboratory measurements prove that among the flexible vegetation under study, purple willow has the biggest modulus of elasticity, followed by common reed, with black alder being the least flexible. In what regards the modulus of non-dilatational strain  $G$ , the relationship is the opposite, i.e. alder has the biggest non-dilatational strain while that of willow is the smallest.

The modulus of elasticity  $E$  after drying (8,000 MPa) almost doubled in comparison with modulus from fresh willow. These values are a bit higher than those cited in literature [25] for dry samples of white willow – 7,200 MPa. For samples taken from two different shrubs of the same species, obtained values were slightly different. For humid plants the difference of the modulus was about 10%, and after drying 20%. However, the differences in values of the variation coefficient for fresh and dry samples were respectively 0.09 and 0.12.

For both willow series the modulus of non-dilatational strain  $G$  was similar. The differences for fresh samples were about 8% and after drying the differences for average value of the modulus was 6%. However the differences in the values of the variation coefficient for fresh and dry samples were respectively 0.18 and 0.14. As with the willow, modulus of elasticity for alder after drying was doubled, while the variation coefficient for fresh and dry samples was reduced by the value 0.12.

Under external forces, plants with hollow stem cross-sections, e.g. reed, disintegrate (the stem breaks). Plants with filled stems (willow, alder) deflect without breaking. Also, in this case significant variability of parameters was observed even for the same plant specimen. Experiments also show that the duration of the phenomenon is important. Experiments carried out on different plant species demonstrate that after the load is applied and the sample is left charged, the strain is not constant but grows with time (Fig. 4). If the load is relieved, the deformation diminishes in time. In this context further research is recommended into the behavior of flexible vegetation subjected to the flow of water in the long-term. The knowledge of elastic recovery will allow us to predict whether after a flood wave plants will be able to return to their natural condition or will they rather break or bend irreversibly. This provides clues as to which floodplain plants can survive a flood wave and what will be their influence on the parameters of flow. The article presents the recovery values for the highest load applied. It appears that after the load is relieved the species with filled stems (willow, alder) have greater strain capacity (elasticity) than the plants with hollow stems (reed). This quality of willow and alder helps them to survive long flooding.

Attempts at general handling of strength parameters of flexible riverbank vegetation may sometimes lead to considerable errors. If not for other reasons, then at least because of the influence of humidity on physical and mechanical properties of vegetation, including, in particular, their flexibility. Proposed methods and measurement set-ups should be understood as a proposal to further develop the methodology of such research in cases where no standards and regulations exist.

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