Assurance of precision for geometric dimensions of trench during pipeline development

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Abstract. The article deals with important issue of keeping precise dimensions of pipeline trench while being developed by chain trench excavator under hard conditions of irregular soil surface. Research done in the article combined modeling of excavator overcoming soil irregularity with experimental tests of the real machine under the initial conditions of model equations. Theoretical predictions were proven by the experimental data and gave a key for the control device algorithm which is supposed to provide necessary precision of trench shape and dimensions.

1. Introduction

The construction of linear facilities for instance of long distance pipelines requires continuous accuracy checking for the geometric dimensions of a trench at a distances of dozens or even hundreds of kilometers. Not only performance of construction operations, but also the proper functioning of the pipeline itself depends on the quality of the operation of pipeline trench development. And since the main pipelines are also industrially hazardous facilities, the relevance of the quality performance of all construction operations is beyond any doubt [1,2,3,4,5].

The main requirements for the geometrical parameters relate to the shape, straightness and slope of the trench and are expressed as the maximum deviations of the various trench parameters from the given in project [6]. To meet the requirements construction rules for trenches during their development for various communication facilities one must provide special devices to keep the walls of the trench from collapse, as well as the perform strengthening of trench slopes.

Usually this is implemented when development goes in non-cohesive soils, for instance sandy loams and when construction goes on directly in the trench [5,6, 7-10, 11-14]. But there are trenches and conditions when recommendations allow construction without restraints and slopes. Example of this case is represented by trenches with vertical walls of up to 3 meters of depth when being worked with rotary and other trench excavators in cohesive soils (loams, clays) [8].

Development of grooves and the basements for foundations and water supply facilities must meet the requirements for construction as well. [15-19]. In this case, these requirements are not applied to the trench , but to the communication placed in it, and are expressed in dimensional tolerances [7,10,15,18,19]:

– allowed deviations of the bottom of the grooves from the required at rough development by trench excavators are ±10 cm;

– allowed deviations of the bottom of the grooves from the required at final development by trench excavators are ± 5 cm;

– allowed deviations of the longitudinal slope of the bottom of the trench under the free-flow pipelines, drainage ditches and other grooves with a slope are ± 0.5‰;

– maximum deviations of the pressure pipelines axes should not exceed ± 100 mm;

– tray markers of free-flow pipelines – ± 5 mm;

– top markers of pressure pipelines – ± 30 mm.

These high requirements make necessary use of innovative and modern means of construction work. [3,20,21]. The highest output of ground works is demonstrated by trench excavator. Taking into account all of the mentioned above requirements for trenches and grooves one can provide vertical walls and smooth bottoms without additional efforts put into smoothing and cleaning of bottom surface[2,4,5,20,22].

2. Formulation of the problem

This paper will discuss the process of building a trench for various purposes using a chain trench excavator (CTE) with work tool (WT) control device in transversal plane (plane which is perpendicular to the direction of motion) that provides necessary quality of construction works. On serial CTEs, only longitudinal position of WT is controlled to obtain a trench of necessary depth and slope level but this type of control cannot guarantee the correct geometric shape of the trench. This may be achieved by compensation of WT deviation from gravitational vertical caused by action of bottom irregularities on WT through the driving and suspension mechanisms. For that special CTE with additional automatic WT control device in transverse plane must be developed.

3. Theory

Special WT motion in transversal plane control algorithm for precise trench construction was worked out for CTE (Fig. 1). The algorithm is designed to determine the sequence and to generate control signals by the control unit when the traveling equipment receives disturbing effect while the machine is moving along an “uneven” ground surface. Work algorithm of the control device takes into account the requirements for the geometric shape of the trench, set of the main parameters of the control device, the performance of the CTE and its geometrical dimensions. All of this in turn allows to determine the sequence of generated control signals from the control unit to the distributors for tilting of WT and to change the speed of motion for of CET during construction works. The work tool of the CTE in the transverse plane is rigidly connected with the platform, therefore the slope of the platform in the transverse plane causes position change in the of the WT.

Correct functioning of the algorithm requires initial conditions for both trench and excavator parameters. For the trench the main of these parameters is angle of WT from vertical with initial value $\gamma=0$ deg. Depth of trench is not stated on this stage because is insignificant. Initial conditions for excavator parameters are: – delay time of hydraulic drive; $X_{control}$ – signal for a distributive control valve of the tilt of WT of CET; $S_{p.max}$ - maximum section area of hydraulic magistral; t_i - tilt sensor polling time interval; R – the radius of the channel flow area of the hydraulic valve; V – CTE speed; t – signal time on valve winding; U_{max} – voltage on valve winding corresponding to the maximum flow channel area; V_{angle} – rate of change of WT angle in transverse plane.

As an example we consider pipeline trench development by CTE TRS 950 BSL Dominik manufactured by Ishim machine plant with ability of track tilt for enhanced quality of trench development in case of irregular bottom surface. Investigation of interaction of construction machine with soil media resulted in development of the mathematical model of the CTE working process. This gave the base for the flowchart of the trench development by CTE. Mathematical model was formalized with following assumptions [4, 12]:

1) only increments of the largest values of generalized coordinates for elements of design scheme are considered;
2) system is represented as multi-link chain, which is depicting frame with mounted engine, transmission, left and right tracks with driving gears and WT. All of these are getting into interaction with soil;
3) WT is fixated with hydraulic cylinder and to the frame and is linked to the frame with rotary joint;
4) multi-link chain elements are rigid;

Given assumptions were taken into account at simplified spatial design scheme for trench development is presented on figure 2.

Basic tractor with mass m_1, including masses of frame, engine, WT drive gear with hoisting mechanism, reduction gear, hydraulic system, track roller, is considered in $O_1X_1Z_1Y_1$. coordinate system. Center of mass of basic tractor is in O_1.

WT with mass m_2, including WT frame mass together with tension device, evacuation screw, transmission chain, cleaning wedge, is parametrized by $O_2X_2Z_2Y_2$ coordinate system. WT center of mass is in O_2.

For calculations in inertial coordinate system $O_0X_0Y_0Z_0$ one must state reference plane going through points O_0X_0 and O_0Y_0.

Distances from this plane and equipment of undercarriage are:

- Y_{FR} – vertical coordinate of front roller of the right track;
- Y_{FL} – vertical coordinate of front roller of the left track;
- Y_{BR} – vertical coordinate of back roller of the right track;
- Y_{BL} – vertical coordinate of back roller of the left track;
- Y_{WB} –change in vertical coordinate of WT in inertial reference frame caused by irregularity of the trench bottom surface.

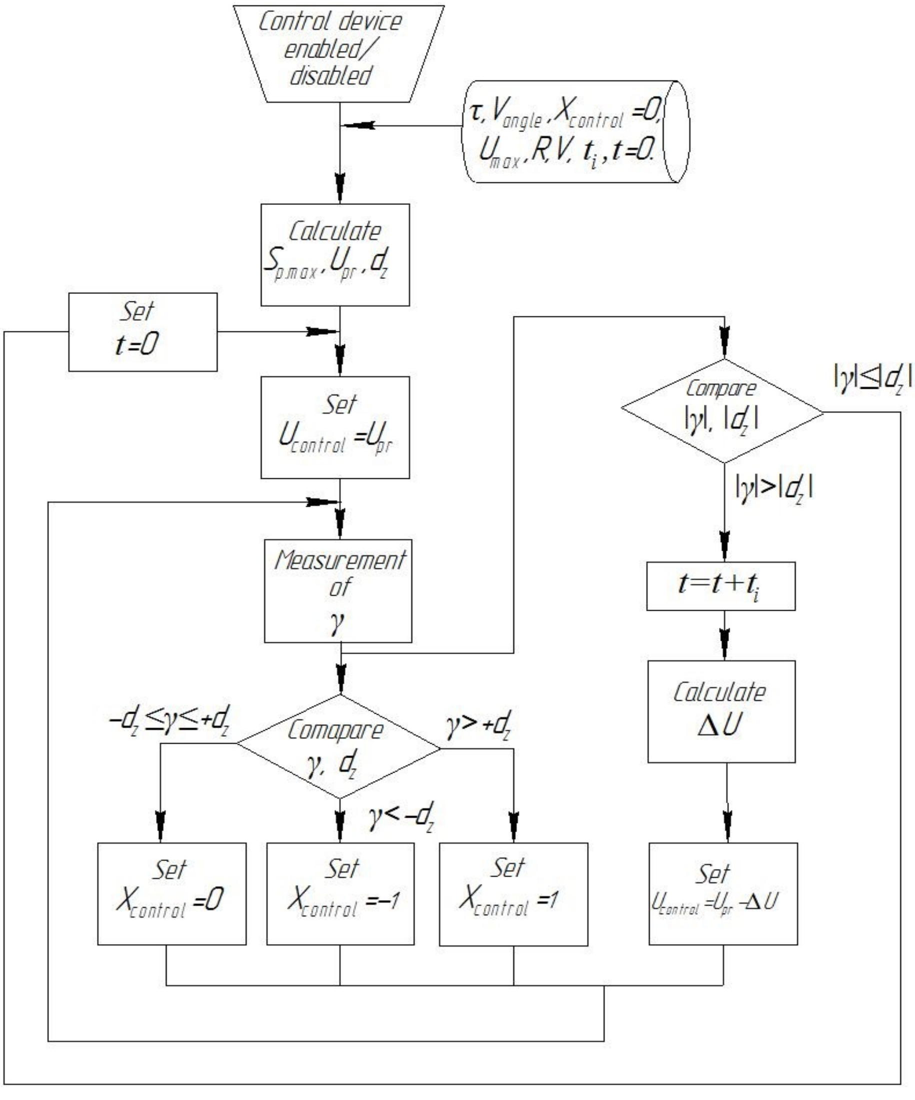

Figure 1. Flow chart of the algorithm for control device designed to provide required geometriv dimensions of the trench.

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Notations on figure 2 are as follows:

- L – length of CTE base;
- L_M – distance from the axes of the drive sprocket to the cutting edge which forms the trench bottom;
- L_{WB} – distance from the axes of the driven sprocket to the cutting edge which forms the trench bottom;
- L_b – width of machine's base;
- Y_{CL} – vertical coordinate of the center of left track;
- Y_{CR} – vertical coordinate of the center of right track;
- Y_C – vertical coordinate of the center of machine;
- ɣ – transvers tilt angle of the machine, caused by irregularity of the trench bottom surface;
- H_T – WT depth of penetration in soil medium;
- $F_{\sigma\ mean}$ – mean reaction force from the soil on WT;
- Q_R, Q_L – reactions of soil on left and right tracks.

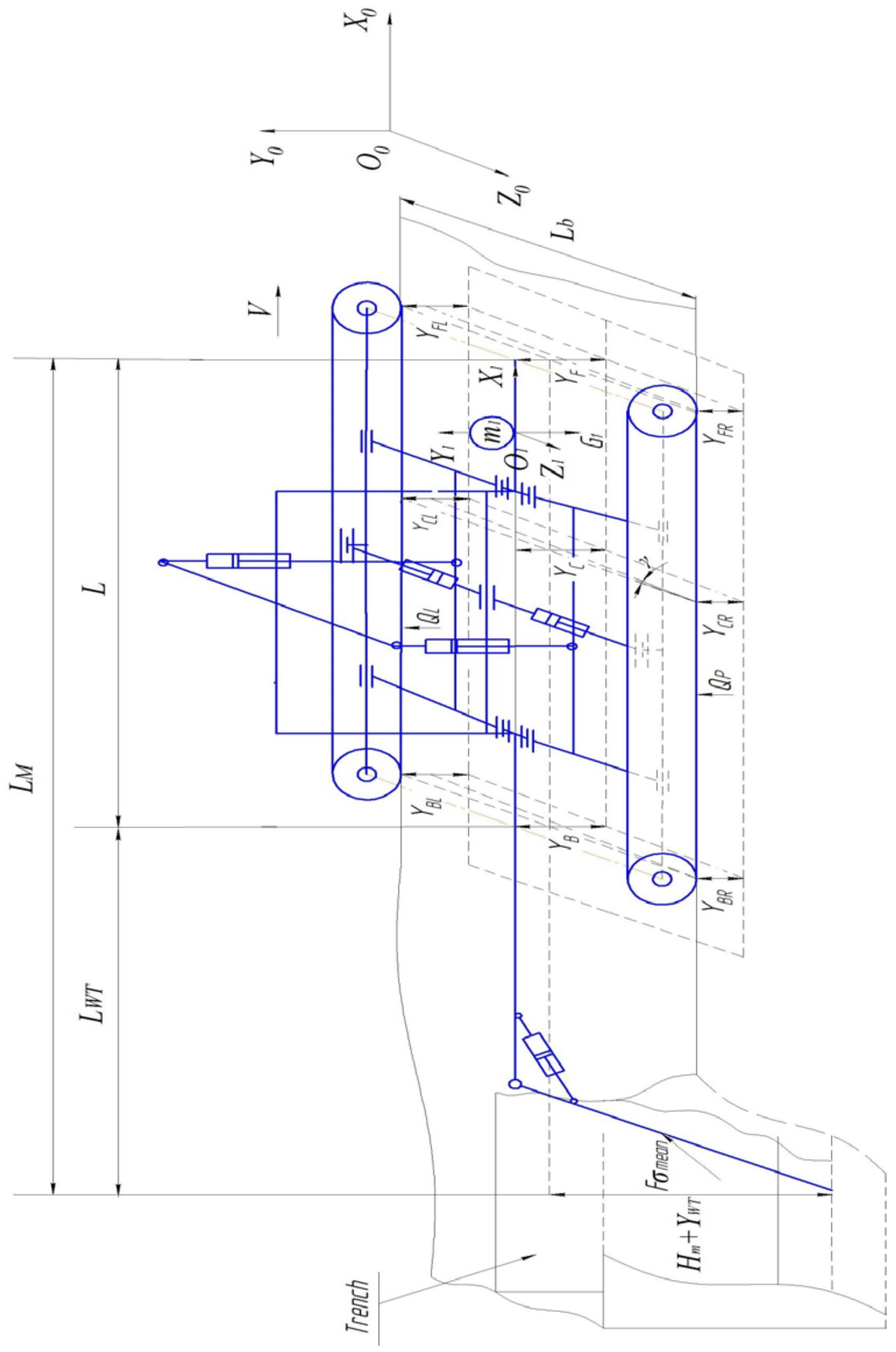

Figure 2. Simplified spatial design scheme of trench development with CTE

Formulas following from scheme on figure 2 are :

$$Y_{CR} = \frac{Y_{FR}+Y_{BR}}{2}, \tag{1}$$

$$Y_{CL} = \frac{Y_{FR}+Y_{BL}}{2}, \tag{2}$$

$$Y_{C} = \frac{Y_{CR}+Y_{CL}}{2}. \tag{3}$$

$$\gamma = sin^{-1}\frac{Y_{CL}+Y_{CR}}{L_b} \tag{4}$$

$$Y_{WB} = \frac{Y_C \cdot L_{WB}}{0.5 \cdot L_b} \tag{5}$$

Relation (4) allows to calculate tilt angle of CTE in transverse plane, relation (5) – change in digging depth of CET caused by the irregularities of the soil surface.

4. Results of experiments

Full range experimental investigation of linear object construction complex approach that includes theoretical methods must be used [22-25]. In situ experiments were done in order to prove theoretical results. Irregularity was modelled by the soil bump 0.2 m high and 2.35 m long. Deviations of the machine caused by shape of irregularities of the soil surface were measured by tilt angle indicator mounted on CTE TRS 950 BSL Dominik (Figure 3).

Figure 3. CTE TRS 950 BSL Dominik

Conditions of the experiment:

1) Excavator moves on the soil surface with constant speed. First part of the experiment consists of treading of the left track on irregularity (made up of soil) while right track is on the horizontal surface (reference plane).
2) At the second part of the experiment right track treads on irregularity (made up of soil) while left track is moving on the horizontal surface (reference plane). Every 5 seconds tilt indicator data are taken (showing deviation of WT from gravitational vertical).
3) Measurement results are saved in the chart (Chart 1). Graphic dependences of the tilt angle of WT on time are drawn (figures 4 and 5).

Chart 1. Tilt angle sensor data for WT in case of irregularity under left and right track

t, s / tilt angle	0	5	10	15	20	25	30	35	38
γ_L, deg	0	1	2,5	4	5	4	3	1	0
γ_R, deg	0	1	2	3	5	4	3	1,3	0

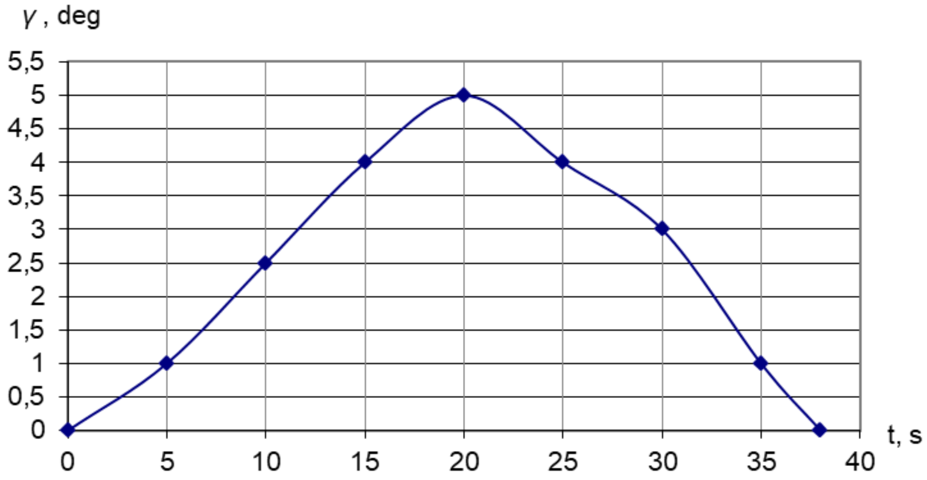

Figure 4. Graph of dependence for WT tilt angle change on time when the left track overcomes soil irregularity (experimental)

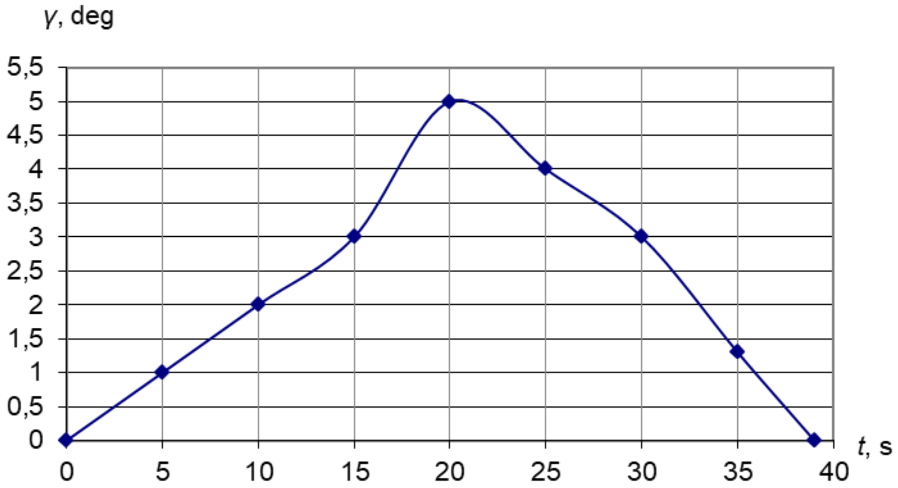

Figure 5. Graph of dependence for WT tilt angle change on time when the right track overcomes soil irregularity (experimental)

4) Experimental data is to be compared to the theoretical prediction. This requires numeric modelling of the process of irregularity overcoming for both trcks of the CTE. For that purpose in the system of equations must be included perturbation formalized as a value of vertical coordinate in the

moments of time corresponding to those when experimental dada were taken. In turn the representation of basic machine was formalized as set of geometric constraint relations given by (1-5).

As a sours of perturbation signal for numeric modelling of irregularity action on CET we used Signal Builder block from Simulink library were the vertical coordinates for the control points on the contact surface of the track are set. According the time of the experiment time period of modelling was set 40 s.

Chart 2. Results of theoretical modeling for motion of left and right track on the soil irregularity

t, s / vert. coordinate	0	5	10	15	20	25	30	35	40
Z_L, m	0	+ 0.03	+0.09	+0.15	+0.2	+0.17	+0.1	+0.04	0
Z_R, m	0	+0.025	+0.085	+0.1	+0.2	+0.15	+0.1	+0.05	0

According to the results that are shown in chart 2 the graphs representing modelled change of the vertical coordinates along irregularity under left and right tracks of moving excavator were drawn. Data of the WT tilt angle indicator for both cases was also obtained.

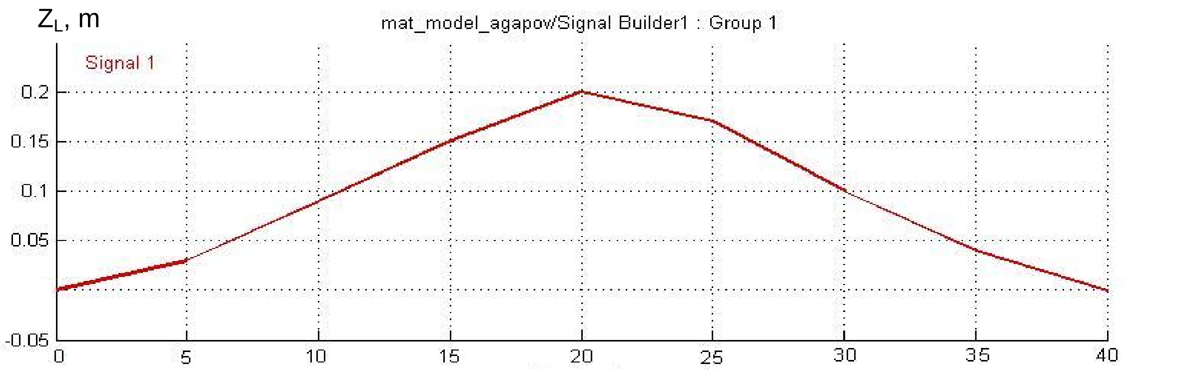

Figure 6. Change of the vertical irregularity coordinate along the left tread (calculated)

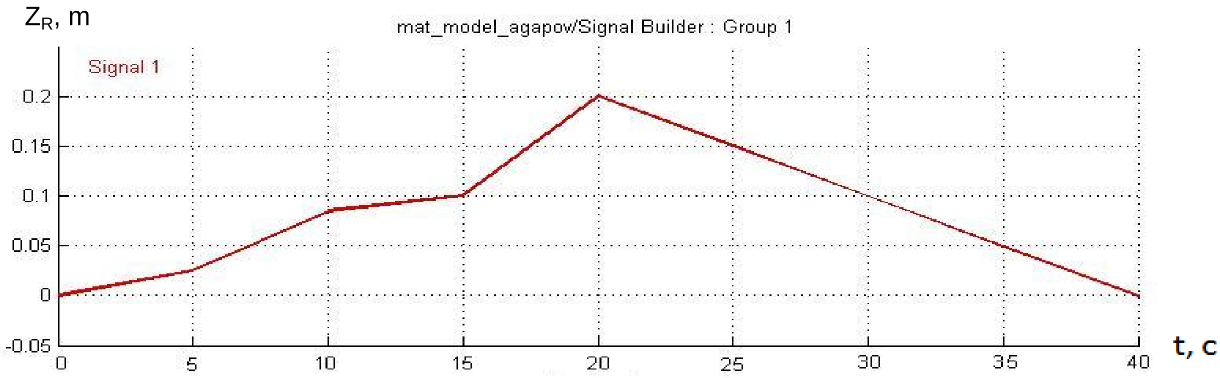

Figure 7. Change of the vertical irregularity coordinate along the right tread(calculated) t, s

Modelling resulted in the set of values for WT tilt angle from gravitational vertical to be compensated in order to achieve correct geometric shape of the trench during development (Chart 3). The chart contains absolute values of the WT tilt angle (without sign) because the base of CTE can have clockwise tilt as well as counterclockwise. Automatic control system although provides positive value and «+» for counterclockwise compensatory tilt and negative value and «-» sign for clockwise rotation.

Chart 3. Results of displacement modelling for the left and right tracks during motion over soil surface irregularity during trench development

№	0	5	10	15	20	25	30	35	40
γ_L, deg	0	0,75	2,24	3,73	4,97	4,23	2,49	1	0
γ_R, deg	0	0,62	2,15	2,49	4,97	3,73	2,49	1,18	0

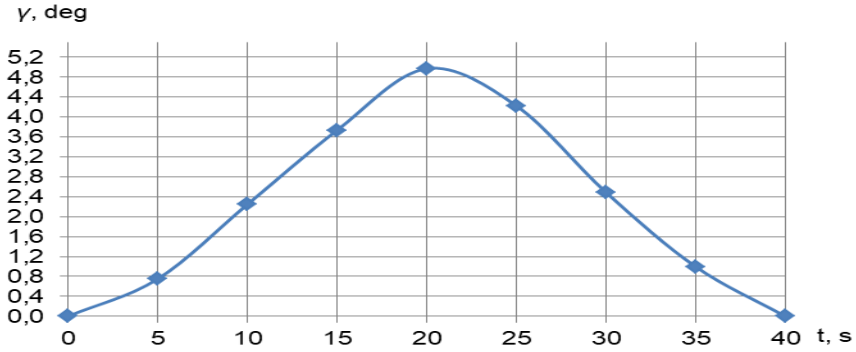

Figure 8. Graph of dependence for WT tilt angle on time for the case of soil irregularity under the left track (calculated)

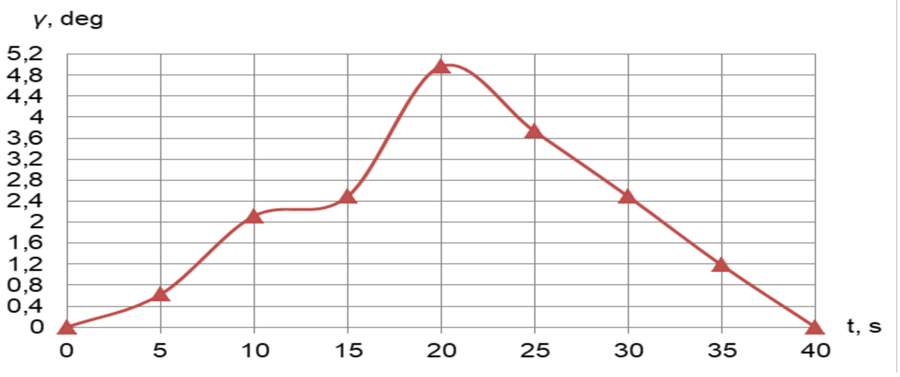

Figure 9. Graph of dependence for WT tilt angle on time for the case of soil irregularity under the right track (calculated)

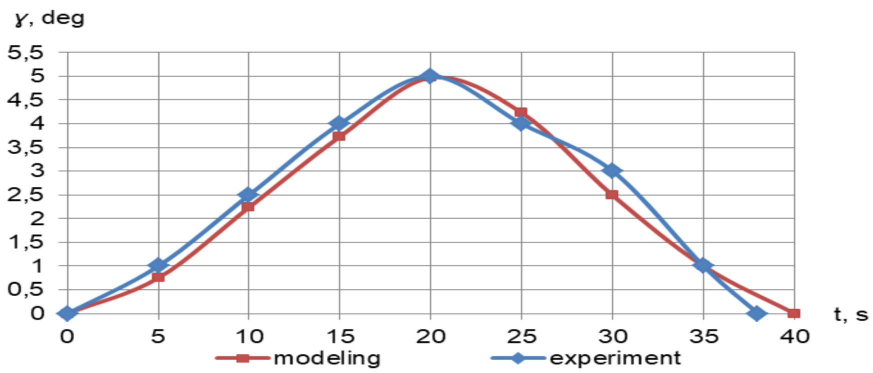

Figure 10. Comparison of modelled and experimental dependences for WT tilt angle on time for the case of soil irregularity under the left track

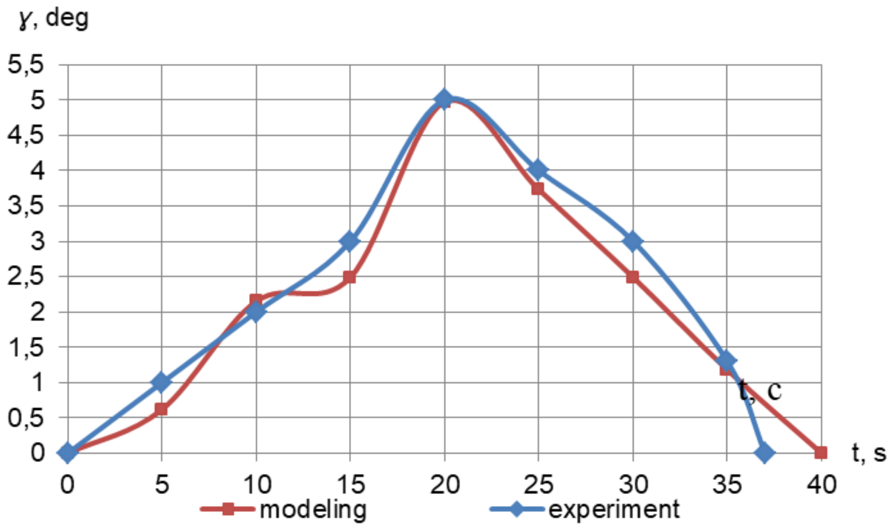

Figure 11. Comparison of modelled and experimental dependences for WT tilt angle on time for the case of soil irregularity under the left track

Differences between experimental data and corresponding values of the tilt values obtained by modelling do not exceed 9 %. This fact proves adequacy of suggested mathematical model of trench development by CTE equipped with automatic control device for WT position in transverse plane.

5. Discussion

As a result of the research presented in article one can encounter that the goal which was set at the starting point was achieved. Experiments have shown the correctness of theoretical consideration for work process of CTE during trench development for pipelines and other transportation and communication facilities. Special control device for automatic compensation of position deviation of WT in transverse plane has shown high efficacy. Use of this device can provide necessary precision of trench development works together with high performance even in case of irregular underlying soil surface.

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