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A STUDY OF THE DEFLECTIONS OF METAL ROAD GUARDRAIL POST

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Abstract. Road guardrails of various types (made of reinforced concrete, cable and metal) are installed on the shoulders and traffic lanes of urban and suburban roads. Metal guardrails, consisting of Σ-shape and double T-shape metal posts and a protective W-shape horizontal beam, are the most popular. The deformation processes of the Σ-shape and double T-shape metal posts of the above-mentioned guardrails are examined. A mathematical model of Σ-shape (or double T-shape) metal post is developed. A metal post of Σ-shape (or double T-shape) is modeled, using one-dimensional first-order finite elements, and taking into account elastic deformations, as well as the effect of soil on the buried post section of the guardrail. The deflections of Σ-shape and double T-shape metal posts caused by the impact of a motor vehicle moving at varying speed are determined.

Keywords: traffic safety, guardrail, beam, post, deflection, motor vehicle, speed, mathematical model, simulation.

1. Introduction

The development of road transport is obviously a positive trend if viewed from the perspective of social and economic benefits it brings. The penetration rate of motor vehicles is increasing every year and, based on the forecasts appearing here and there in press, it will only continue to grow. Though viewed as a positive trend, within a society the growth of motor vehicle penetration rate, unfortunately, brings about a number of negative effects, with the rate of traffic accidents standing as the most critical one. Based on the world-wide statistics (Prentkovskis *et al.* 2007; 2008; 2009; 2010), about 700 thousand people are killed, 20 million get injured in traffic accidents each year. According to the Accident Rate Information, in Lithuania, the Traffic Police recorded 3827 road accidents in 2009, which appeared in the official statistics under any of the following categories (Prentkovskis *et al.* 2009; 2010):

- a motor vehicle hitting a pedestrian (35.1%);
- a motor vehicle hitting a bicyclist (7.5%);
- a collision of motor vehicles (33.4%);
- motor vehicle turnover (9.3%);
- collision of a motor vehicle with an obstacle (7.6%);
- other road accidents (7.1%).

According to the same statistical data (Prentkovskis *et al.* 2009), the collision of a motor vehicle with an obstacle accounts for about 8% of all traffic accidents recorded in Lithuania (see also Accident Rate Information). In this case, the obstacle may be represented by a road guardrail, lighting pole, railway switch, tree, gate or any building or structure located near the road, etc.

All factors influencing the rate of traffic accidents are divided into three groups: people (drivers, cyclists, carters, pedestrians, passengers, etc.); motor vehicles (cars, buses, trolleybuses, motorcycles, scooters, mopeds, bicycles etc); roads and streets.

It is considered that 2/3 of all road accidents occur due to the fault of the people and only 1/3 due to factors, which do not depend on the will and actions of people (Prentkovskis, Bogdevičius 2005). It is shown by the statistical data. The main causes of accidents according to their frequency are: strong driver's errors (65%); poor road conditions (23%); technical defects of motor vehicles (12%). The types of traffic users, who caused accidents according to different categories include: drivers (53%); pedestrians (32%); cyclists (9%); carters (6%).

According to the data of Lithuanian Road Administration under the Ministry of Transport and Communications of the Republic of Lithuania, there is a highly developed network of roads of national significance (total 21320 km) in the country, including main roads (8%); national roads (23%); regional roads (69%).

As mentioned above, one of the types of road accidents is hitting an obstacle. The obstacle may be a road

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guardrail which is mounted on the dangerous road sections (e. g. near a sharp turn, as well as the objects on the roadside, bridges, viaducts, etc.).

2. Purposes of road guardrails and overview of research studies

As known by Elvik *et al.* (1997) and Prentkovskis *et al.* (2007, 2008, 2009) researches, various types of safety guardrails are intended for reducing the damage caused by traffic accidents rather than avoiding accidents.

The function of road guardrails or their elements (band and post) is to reduce the probability for a motor vehicle to violate the traffic by keeping it within roadway limits and by guiding its travel along the longitudinal axis of the guardrail and/or fully stopping it. To enable the aforementioned functions, the guardrails are designed in such a way as to ensure full or partial absorption of the motor vehicle's kinetic energy due to the deformation of the guardrail structural elements (band and post), occurring at certain specific accelerations developed during an impact (Prentkovskis *et al.* 2007; 2008; 2009).

The elements of a metal road guardrail may be described as a beam system and analysed with the use of finite elements and various software packages (for example, *ANSYS*, *ALGOR*, *LS-DYNA,* etc).

The deformation processes of such a system (for example road guardrail) may be approached as a separate object (Prentkovskis, Bogdevičius 2005; Prentkovskis *et al.* 2007; 2008; 2009) or analysed by integrating it into transport infrastructure, whose constituent parts are described in the papers of Atahan (2004), Atahan *et al.* (2008), Antov *et al.* (2009), Beljatynskij *et al.* (2009), Dragčević *et al.* (2009), Elvik *et al.* (1997), Gowri and Sivanandan (2008), Junevičius and Bogdevičius (2009), Kinderytė-Poškienė and Sokolovskij (2008), Macek and Měšťanová (2009), Mohan *et al.* (2005), Nagurnas *et al.* (2008), Polivka *et al.* (2007 and 2008), Prentkovskis and Sokolovskij (2008), Reid *et al.* (2009), Sokolovskij *et al.* (2007), Tan *et al.* (2008), Tautkus and Bazaras (2007), Vansauskas and Bogdevičius (2009), Viba *et al.* (2009), Vorobjovas and Žilionienė (2008), Wu and Thomson (2007), etc.

Prentkovskis and Bogdevičius (2005) presented and investigated the mathematical model of a deforming road guardrail, Prentkovskis *et al.* (2007; 2008) presented the investigation of potential deformations which could develop in the elements of motor vehicle and pedestrian traffic restricting gates during motor vehicle–gate interaction, and Prentkovskis *et al.* (2009) examine the deformation processes of the guardrail elements (a protective W-shape horizontal beam and a Σ-shape post).

The potential to increase the suggested flare rates for strong posts, W-beam guardrail systems and thus reduce guardrail length was investigated by Reid *et al.* (2009).

Atahan (2004) presented the results of an experimental study aimed to assess the suitability of a recycled content guardrail post as a substitute for conventional wooden guardrail post.

In next research, Atahan *et al.* (2008) developed European end-treatment using simulation and crash testing. A simple guardrail end-treatment, called TWINY, designed particularly for the use with a Thrie-beam guardrail system is developed. The TWINY is analyzed using a versatile, highly non-linear finite element analysis program *LS-DYNA*.

Tan *et al.* (2008) analysed motorcyclist-friendly guardrail using the finite element method. The event of collision between the motorcycle and the guardrail was then simulated using the computer finite element program – *ALGOR*.

For longitudinal guardrails it is a common practice to use a standard W-beam guardrail along the required highway sections and a stiffened Thrie-beam guardrail in a transition region near the end of a bridge (Polivka *et al.* 2007). The model of a guardrail transition system, including the W-beam to Thrie-beam transition element, was constructed and crash tested.

A W-beam guardrail is often used to protect motorists from steep roadside slopes adjacent to high-speed roadways (Polivka *et al.* 2008). The presented guardrail design was provided to safe and economical alternative for the use along the highways with steep slopes located very close to the carriageway.

Wu and Thomson (2007) submitted a study of the interaction between a guardrail post and soil under the quasi-static and dynamic loading for simulation of *LS-DYNA* software.

Mohan *et al.* (2005) submitted the research into finite element modelling and validation of a Three-strand cable guardrail system.

Traffic safety problems, such as the interaction between a motor vehicle and road guardrails, motor vehicle dynamics and guardrails of various types were investigated in different time periods by Antov *et al.* (2009), Beljatynskij *et al.* (2009), Boumediene *et al.* (2009), Çalışkanelli *et al.* (2009), Cansiz and Atahan (2006), Coon and Reid (2005), Dragčević *et al.* (2009), Elvik *et al.* (1997), Ibitoye *et al.* (2006), Junevičius and Bogdevičius (2009), Kapski *et al.* (2008), Kinderytė-Poškienė and Sokolovskij (2008), Lazda and Smirnovs (2009), Macek and Měšťanová (2009), Nagurnas *et al.* (2008), Pelenytė-Vyšniauskienė and Jurkauskas (2007), Prentkovskis *et al.* (2007; 2008; 2009), Sokolovskij *et al.* (2007), Šliupas (2009), Tautkus and Bazaras (2007), Vansauskas and Bogdevičius (2009), Viba *et al.* (2009), Vorobjovas and Žilionienė (2008), etc.

The authors of this paper are also engaged in research associated with the considered problems. The model of the post of the beam metal road guardrail, presented in this paper, is a part of the general mathematical model "road–motor vehicle–obstacle" (Prentkovskis *et al.* 2007; 2008; 2009; Prentkovskis, Bogdevičius 2005).

The authors of the present paper examined the deformation processes of the Σ-shape and double T-shape metal post of a metal guardrail (Fig. 1).

3. A brief description of the mathematical model of metal road guardrail post

To study the potential deformations of the posts of metal road guardrails, a mathematical model of a beam system

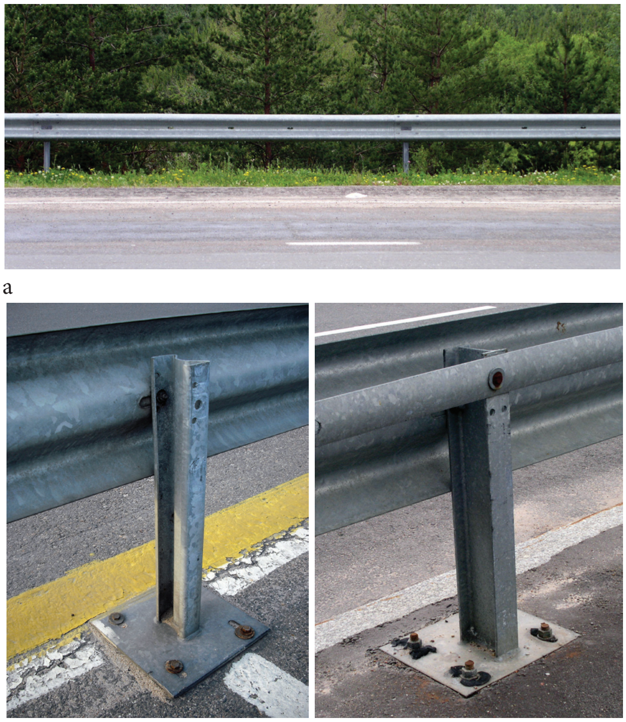

Fig. 1. A metal guardrail: a – a general view of the road (W-shape horizontal beam and posts); b – a Σ-shape post; c – a double T-shape post (Prentkovskis *et al.* 2009)

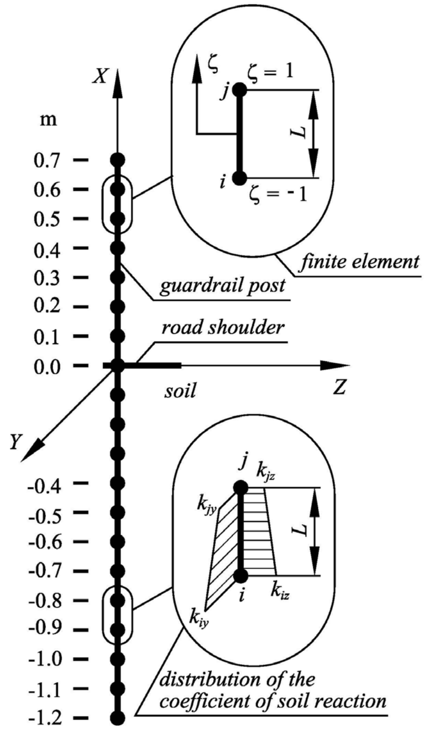

Fig. 2. A schematic view of the metal guardrail post and one-dimensional first-order finite element, and distribution of the coefficient of soil reaction

was developed (Prentkovskis, Bogdevičius 2005; Prentkovskis *et al.* 2009). A metal road guardrail post (Fig. 1b or Fig. 1c) was modelled by using one-dimensional first-order finite elements (Fig. 2). In the interaction between a motor vehicle and a guardrail post, the nodes of the finite elements change their position in the system of the coordinates used (the elements are deformed).

In simulation, only elastic deformations and the effect of soil on the buried post section of the guardrail are taken into account.

When mounting guardrails, their posts are dug into soil or concreted, for example, on bridges or viaducts. Therefore, when studying the deformation process of the guardrail posts, the impact of soil shall be taken into consideration. For this purpose, the coefficient of soil reaction, which evaluates the impact of soil (or asphalt concrete) on the buried post section of guardrail, is used (Fig. 2):

$$k(x) = k_0 + k_1 x, \tag{1}$$

where $k_0 = k_i$; $k_1 = \dfrac{k_j - k_i}{L}$.

The system of the equations for the finite element movement is obtained in the form of a matrix:

$$\left[M^{(e)}\right]\left\{\ddot{q}^{(e)}\right\} + \left[C^{(e)}\right]\left\{\dot{q}^{(e)}\right\} + \left[K^{(e)}\right]\left\{q^{(e)}\right\} = \left\{F^{(e)}\right\}, \tag{2}$$

where $\left[M^{(e)}\right]$, $\left[C^{(e)}\right]$, $\left[K^{(e)}\right]$ – the matrices of masses, damping of the mechanical energy and stiffness of the finite element; $\left\{\ddot{q}^{(e)}\right\}$, $\left\{\dot{q}^{(e)}\right\}$, $\left\{q^{(e)}\right\}$ – vectors of generalized accelerations, speeds and displacements of the finite element; $\left\{F^{(e)}\right\}$ – the vector of generalized forces acting on the finite element.

By integrating the equations of movement of all finite elements into a unified system, a system of road guardrails post movement is obtained:

$$\left[M_{post}\right]\left\{\ddot{q}_{post}\right\} + \left[C_{post}\right]\left\{\dot{q}_{post}\right\} + \left[K_{post}\right]\left\{q_{post}\right\} = \left\{F_{post}\right\}, \tag{3}$$

where $\left[M_{post}\right]$, $\left[C_{post}\right]$, $\left[K_{post}\right]$ – the matrices of masses, damping of mechanical energy and stiffness of a guardrail post; $\left\{\ddot{q}_{post}\right\}$, $\left\{\dot{q}_{post}\right\}$, $\left\{q_{post}\right\}$ – the vectors of generalized accelerations, speeds and displacements of all nodes of a guardrail post; $\left\{F_{post}\right\}$ – the vector of generalized forces acting on the road guardrail post:

$$\left[M_{post}\right] = \sum_{e=1}^{NE}\left[M^{(e)}\right];$$

$$\left[C_{post}\right]=\sum_{e=1}^{NE}\left[C^{(e)}\right];$$

$$\left[K_{post}\right]=\sum_{e=1}^{NE}\left[K^{(e)}\right];$$

$$\left\{F_{post}\right\}=\sum_{e=1}^{NE}\left\{F^{(e)}\right\};$$

$$\left\{\ddot{q}_{post}\right\}=\sum_{e=1}^{NE}\left\{\ddot{q}^{(e)}\right\};$$

$$\left\{\dot{q}_{post}\right\}=\sum_{e=1}^{NE}\left\{\dot{q}^{(e)}\right\};$$

$$\left\{q_{post}\right\}=\sum_{e=1}^{NE}\left\{q^{(e)}\right\}, \tag{4}$$

where *NE* – the number of finite elements.

The following parameters of the finite element, including:

- matrix of masses $\left[M_{post}\right]$;
- matrix of damping of mechanical energy $\left[C_{post}\right]$;
- matrix of stiffness $\left[K_{post}\right]$;
- vector of generalized accelerations $\left\{\ddot{q}_{post}\right\}$;
- vector of generalized speeds $\left\{\dot{q}_{post}\right\}$;
- vector of generalized displacements $\left\{q_{post}\right\}$;
- vector of generalized forces $\left\{F_{post}\right\}$ are expressed in the local system of the coordinates. Then, matrices and vectors are transformed into a global system of the coordinates.

4. The results obtained in computer-run simulation

The deformation processes of metal road guardrail Σ-shape (Fig. 1b) and double T-shape (Fig. 1c) posts caused by the impact of a motor vehicle moving at varying speed were examined.

The computer-run simulation was performed on a personal computer using *Intel® Visual Fortran* software.

Usually, guardrail posts are anchored in gravel at the roadside, or their fastening elements are concreted into the structure of bridges and viaducts.

According to specifications and recommendations presented in *Building Recommendations R 37-01. Automobile Road Guardrails*, the following guardrail post parameters were chosen (Fig. 3):

- height of the guardrail post above the road surface – 750 mm;
- height of the buried guardrail post section (when the post is mounted on road shoulder) – 1200 mm;

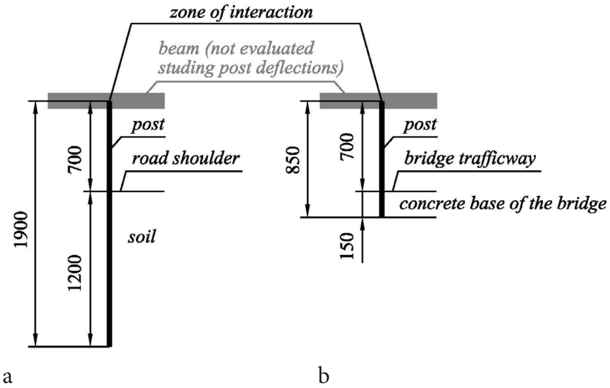

Fig. 3. A schematic view of the metal guardrail post mounted on: a – the road shoulder; b – a bridge (or viaduct)

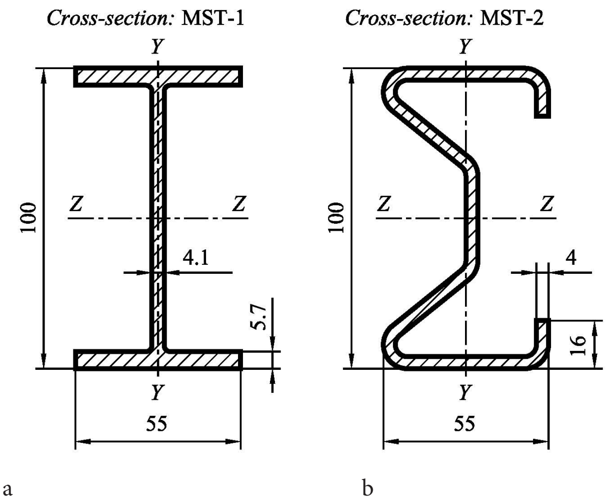

Fig. 4. Cross-sections of a metal guardrail post of: a – double T-shape; b – Σ-shape

- height of the concreted guardrail post section (when the post is mounted on a bridge) – 150 mm;
- cross-section of the guardrail post – double T-shape (MST-1), Σ-shape (MST-2) (Fig. 4).

The following conditions of motor vehicle interaction with a guardrail post were chosen:

- type of motor vehicle – a car;
- mass of the chosen motor vehicle – 1500 kg;
- speed of the chosen motor vehicle – 50 km/h and 90 km/h.

The results obtained in computer-run simulation (deflections of metal road guardrail posts caused by the impact of a motor vehicle moving at varying speed) are presented in Fig. 5.

Based on the dependences presented, it may be noted that the deformation of Σ-shape post is not so heavy compared to double T-shape post deformation. This property of Σ-shape post can be observed in cases irrespective of the post location (on the road shoulder or on the bridge) or the motor vehicle's speed at the moment of collision.

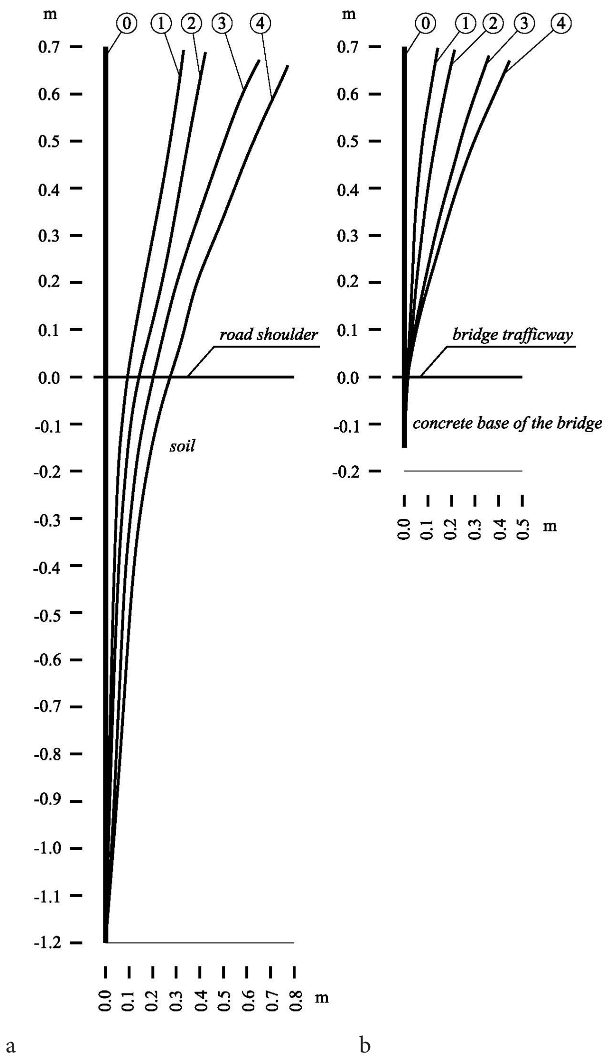

Fig. 5. Deflections of the metal road guardrail posts caused by the impact of a motor vehicle moving at varying speed: a – for guardrail posts mounted on road shoulder; b – for guardrail posts mounted on a bridge (or viaduct); ⓪ – before interaction; ① – cross-section is of double T-shape, after interaction, the speed of the motor vehicle is 50 km/h; ② – cross-section is of Σ-shape, after interaction, the speed of the motor vehicle is 50 km/h; ③ – cross-section is of double T-shape, after interaction, the speed of the motor vehicle is 90 km/h; ④ – cross-section is of Σ-shape, after interaction, the speed of the motor vehicle is 90 km/h

5. Conclusions

A mathematical model of a metal road guardrail post was developed and solved. A guardrail post was modelled using one-dimensional first-order finite elements in the presented post model elastic deformations and the effect of soil on the buried post section of the guardrail are taking into account. Plastic deformations are not taken into account.

A computer-aided experiment (mathematical model solution) was conducted the application programs based on software packages *Intel® Visual Fortran* were used.

The results of the computer-aided experiment, reflecting the deformations of two (Σ-shape and double T-shape) types of posts, are shown graphically. Based on the dependences presented, it may be noted that the deformation of Σ-shape post is not so heavy compared to the double T-shape post deformation. This property of Σ-shape post can be observed in cases irrespective of the post location (on the road shoulder or on the bridge) or the motor vehicle's speed at the moment of collision.

It is widely known that the function of road guardrails or their elements (band and post) is to reduce the probability for a motor vehicle to violate the traffic by keeping it within the roadway limits and by guiding its travel along the longitudinal axis of the guardrail and/or fully stopping it. This may be achieved by using road guardrails or their elements (band and post) having high deformation behaviours, for example the Σ-shape post.

Presented model of a guardrail post may be used by traffic safety specialists and designers of new highways. It may be also useful for implementing reconstruction of old motor roads and analyzing traffic accidents.

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