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A Short Survey of Scientific Results of Academician Andria Bitsadze

"It is too difficult to write about a scientist not only because of the great responsibility toward the history of science, but also because of the complexity of scientific creative process without which it is impossible to show his real personality".

A. Bitsadze

Such an attitude of Andria Bitsadze to the problem cited in the epigraph is not accidental; a task to give an exhaustive description of his versatile activities seems to us insuperable. The true appraisal of human creativity and its crystallization occurs in the future generations. This point of view has been shared by A. Bitsadze. However, his creative work during his lifetime was properly evaluated by the mathematical community. This is confirmed at least by the fact that in the mathematical literature we are often encountered with the facts and terms associated with his name: Bitsadze's equation, Lavrent'ev–Bitsadze's equation, Bitsadze's general mixed problem, Bitsadze's extremum principle, Bitsadze's inversion formula, weakly and strongly connected Bitsadze's elliptic systems, Bitsadze–Samarski's problem, and others. We do not intend to touch upon his organizational, pedagogical or educational work with students, we will dwell only on his scientific results not pretending to present them in a perfect form.

We consider it appropriate to divide Andria Bitsadze's activity into several staged, keeping here chronology.

Elliptic equations and systems together with the problems posed for them take central place in Andria Bitsadze's creative work.

The fact that the condition of uniform ellipticity

$$k_0\Big(\sum_{i=1}^n \lambda_i^2\Big)^N \le \det \sum_{i,j=1}^n A^{ij}(x)\lambda_i\lambda_j \le k_1\Big(\sum_{i=1}^n \lambda_i^2\Big)^N, \quad k_0,k_1 = const > 0,$$

of the linear equation, or of the system

$$L(u) := \sum_{i,j=1}^n A^{ij}(x)\,\frac{\partial^2 u}{\partial x_i \partial x_j} + \sum_{i=1}^n B^i(x)\,\frac{\partial u}{\partial x_i} + C(x)u = F(x), \ \ u = (u_1,\dots,u_N)$$

ensures fredholmity of the boundary value problems in the domain D, in particular, of the first boundary value problem

$$u\big|_{\partial D} = f,$$

was assumed formerly indisputable.

Irregularity of this fact was illustrated by A. Bitsadze in a simple and clear for everyone example, called later on Bitsadze's system

$$\frac{\partial^2 u_1}{\partial x^2} - \frac{\partial^2 u_1}{\partial y^2} - 2\,\frac{\partial^2 u_2}{\partial x \partial y} = 0, \quad 2\,\frac{\partial^2 u_1}{\partial x \partial y} + \frac{\partial^2 u_2}{\partial x^2} - \frac{\partial^2 u_2}{\partial y^2} = 0. \tag{1}$$

It turned out that the Dirichlet homogeneous problem for Bitsadze's system in a circular domain $D:\ (x-x_0)^2 + (y-y_0)^2 < R^2$ has an infinite set of linearly independent solutions, and all of them are representable explicitly by the formula

$$w := u_1 + iu_2 = \big(R^2 - |z-z_0|^2\big)\psi(z), \ \ z_0 = x_0 + iy_0$$

written in terms of an arbitrary analytic function $\psi(z)$ of the complex argument $z = x + iy$.

While this fact seemed unexpected and almost improbable, it became a subject of discussions for many mathematicians trying to explain this phenomenon. At his known seminar, I. Gelfand made an attempt to explain this fact by multiplicity of characteristic roots of system (1). In reply, A. Bitsadze has constructed another system

$$\frac{\partial^2 u_1}{\partial x^2} - \frac{\partial^2 u_1}{\partial y^2} + \sqrt{2}\,\frac{\partial^2 u_2}{\partial x \partial y} = 0, \quad \sqrt{2}\,\frac{\partial^2 u_1}{\partial x \partial y} - \frac{\partial^2 u_2}{\partial x^2} + \frac{\partial^2 u_2}{\partial y^2} = 0 \tag{2}$$

with simple characteristic roots, the system for which the Dirichlet problem has likewise an infinite set of linearly independent solutions

$$w_k(z) = B_k\Big\{\big[(\mu\zeta + \overline{\zeta})^2 - 4\mu R^2\big]^k - (\mu\zeta - \overline{\zeta})^{2k}\Big\}, \quad k = 1, 2, \dots,$$

where $\zeta = z - z_0$, $(1 + \sqrt{2})\mu = i$, and B_k are arbitrary complex constants. On the basis of those simple and refined examples, the theory of boundary value problems for elliptic systems has acquired a great deal of new trends. The widely known theory of nonfredholm boundary value problems is one of such them. These theories do not lose their importance even nowadays, and many of A. Bitsadze's followers and pupils devote them their researches.

Afterwards, there arose the natural question to single out classes of elliptic systems with solvable, in a certain sense, boundary value problems, in particular, solvable in the Fredholm, Noether or Hausdorff sense. In this direction, it is impossible to hold back about the question on weakly connected Bitsadze's systems for which the Dirichlet problem is always fredholmian one.

It was considered earlier that solvability of boundary value problems is determined only by the principal part of the system. A. Bitsadze has expressed somewhat different opinion that coefficients of the system with lower order derivatives may significantly affect the solvability of the problem. To justify this concept, he introduced the notion of strongly connected elliptic systems that cover systems (1) and (2) constructed earlier in the form of particular examples. As it has become clear, the solvable in one or another sense boundary value problems for elliptic systems with Bitsadze's operators in the principal part may turn out to be unsolvable on adding the lower order terms.

The above-mentioned fundamental effects were discovered by A. Bitsadze by using the apparatus of the theory of functions of a complex variable. This instrument is well suited for a homogeneous system consisting only of the principal part

$$A\,\frac{\partial^2 u}{\partial x^2} + 2B\,\frac{\partial^2 u}{\partial x \partial y} + C\,\frac{\partial^2 u}{\partial y^2} = 0 \tag{3}$$

with two independent variables. A. Bitsadze has constructed a general regular solution of system (1) in the form

$$u(x,y) = \operatorname{Re}\sum_{j=1}^{n}\sum_{l=1}^{k_j}\sum_{k=0}^{l-1} C_{lkj}\,\overline{z}_j^{\,k}\varphi_{jl}^{(k)}(z_j),$$

where $\varphi_{jl}(z_j)$ are analytic functions of the complex variable $z_j = x + \lambda_j y$, and λ_j are the roots of the corresponding to system (3) characteristic polynomial $Q(\lambda) = \det(A + 2B\lambda + C\lambda^2)$ with positive imaginary parts. As regards the N-component vectors C_{lkj}, they are the solutions of the fully defined system of linear algebraic equations.

The instruments of the theories of analytic functions and of one-dimensional singular integral equations make it possible to investigate many boundary value problems in the case of two independent variables. If there are more than two variables, then there arise considerable difficulties due to the lack of a complete theory of multidimensional singular integral equations. Using a multidimensional analogue of the Sokhotski–Plemelj theorem, A. Bitsadze has studied the first boundary value problem for the well-known Moisel–Theodorescu system, reduced it to a multidimensional system of singular integral equations with a special matrix kernel and constructed the inversion formula which in the literature is called "Bitsadze's inversion formula".

Among the problems formulated for elliptic equations and systems, even, in particular, for harmonic functions, the problem with an oblique derivative is regarded as one of the basic ones, when on the boundary of the n-dimensional domain D there is the condition

$$\sum_{i=1}^{n} \ell_i(x)\,\frac{\partial u}{\partial x_i} = f(x), \quad x \in \partial D.$$

As far back as in G. Giraud's works it has been shown that if the direction of the vector $\ell := (\ell_1, \dots, \ell_n)$ at none of the boundary points meets the tangent, the problem becomes solvable in Fredholm's sense. Otherwise, the situation changes insomuch that many scientists were inclined to consider this problem atypical for elliptic equations. Considering these nonstandard cases, A. Bitsadze has shown this problem not at all to exceed the bounds of typical problems and proved the theorems on a number and existence of solutions. As it has become clear, the problem with an oblique derivative may turn out to be simultaneously subdefinite and overdetermined. For the problem to be well-posed, it is necessary, proceeding from the structure of interconnection between the vector field ℓ and the domain, to release some set of boundary points from the conditions and impose additional conditions on some set of points. To illustrate this, we consider one simplest example when the vector field meets the boundary at k isolated points. In this case a number of linearly independent solutions of the problem under consideration does not exceed k.

The objects of A. Bitsadze's investigations are not always ordinary. He studied the problems which are, as a rule, not subjected to the standard conditions ensuring the existence and uniqueness of solutions. To such problems may belong those suggested by A. Bitsadze for elliptic equations with parabolic degeneration with weighted conditions on the boundary. These problems were dictated by their practical necessity. For such problems not only the conditions of uniform or strong ellipticity violate, but they degenerate parabolically either on the whole boundary, or on its certain part. In addition, a set of points of parabolic degeneration may turn out to be even a characteristic. For example, for the equation

$$\frac{\partial^2 u}{\partial x^2} + y^m\,\frac{\partial^2 u}{\partial y^2} + a\,\frac{\partial u}{\partial x} + b\,\frac{\partial u}{\partial y} + cu = 0, \quad y > 0, \quad m > 0,$$

the line of degeneration $y = 0$ is simultaneously its multiple characteristic. In such a case, the role of coefficients with the lower order derivatives extends, and depending on them, not all solutions may be bounded. M. Keldysh considered this problem in the class of bounded functions, and hence neglected unbounded solutions. A. Bitsadze replaced the requirement of the boundedness by the following weighted boundary conditions:

$$u\big|_\sigma = f, \quad \lim_{y\to 0} \psi(x,y)u(x,y) = \varphi(x), \ \ 0 \le x \le 1,$$

where $\sigma \cup \{y = 0,\ 0 \le x \le 1\}$ is the boundary of the domain, and the weighted function ψ on the line of degeneration vanishes. These problems have brought to light new practical and theoretical validity of weighted functional spaces that before and after formulation of those problems have become the subject of a great number of research works.

The hyperbolic equations and systems aren't less rich with the effects connected with parabolic degeneration. Many factors affect the solvability of the problems formulated here; they include an order of parabolic degeneration, orientation of a set of degeneration points with respect to characteristic manifolds, etc. As distinct from a separately taken equation, hyperbolic systems show a lot of unexpected properties even without parabolic degeneration. Thus, for example, the well-known Goursat problem for a scalar equation is quite well-posed. The constructed by A. Bitsadze hyperbolic system

$$\frac{\partial^2 u_1}{\partial x^2} + \frac{\partial^2 u_1}{\partial y^2} + 2\,\frac{\partial^2 u_2}{\partial x \partial y} = 0, \quad 2\,\frac{\partial^2 u_1}{\partial x \partial y} + \frac{\partial^2 u_2}{\partial x^2} + \frac{\partial^2 u_2}{\partial y^2} = 0$$

has shown that the corresponding homogeneous problem may have an infinite set of linearly independent solutions, and what is more, the lower order terms of the system may affect significantly the well-posedness of the problem. This fact has given a great impetus to many important researches and stimulated the development of a series of scientific trends.

In the middle of the past century, mathematics has found new significant applications that should, seemingly, be explained by an unprecedented rate of technical progress. The major achievements in transonic and supersonic velocities have drawn attention of scientists to many problems, including those of mixed type equations in which M. Lavrent'ev has shown spacial interest and awoken it in A. Bitsadze. Combining the methods of the theory of analytic functions, of partial differential equations and singular integral equations, A. Bitsadze created a powerful and, at the same time, elegant apparatus, convenient for solving the problems formulated for the mixed type equations. Effectiveness of the suggested method has been tested on the boundary value problems for the Lavrent'ev–Bitsadze's equation

$$\frac{\partial^2 u}{\partial x^2} + \operatorname{sgn} y \, \frac{\partial^2 u}{\partial y^2} = 0$$

being the model of the well-known Tricomi's equation for which A. Bitsadze posed a great number of actual problems and established a series of significant facts known in the literature as "Bitsadzian facts". Here we will mention only Bitsadze's extremum principle. For the Tricomi's equation

$$y \, \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0,$$

along with the Tricomi's problem has also been considered the Dirichlet problem expecting its solvability. This was needed, mainly, for practical, concrete purpose.

A. Bitsadze has shown that this problem was not always well-posed, and for it to be solvable, it was necessary to release a definite part of the boundary of hyperbolic subdomain from the conditions. To formulate the problems responding practical purposes in which the whole boundary is occupied with the conditions, A. Bitsadze suggested several versions. In one of his versions he linked the solution values at different boundary points with the functional law. This nonlocal problem is well-posed. It has prompted the ways of its natural generalization to a multidimensional case.

To every well-posed plane problem there may be assigned several spatial versions, of which we will dwell only on those which maximally approach practical problems. The spatial version of the above-mentioned problem of exactly such a nature is easily generalizable and provides us with a well-posed problem. As concerns the Tricomi's problem, it has several generalization versions that make it possible to demonstrate the structure of a set of type variation points. This set of points may turn out to be a surface, oriented to the space and time. This moment determines two essentially different trends in the theory of boundary value problems for multidimensional mixed type equations.

Equations refer to different types, depending on their characteristic roots. If the equation, along with its real characteristic roots, has complex ones, then it belongs to the composite type equations. Such equations include, for example, the Laplace differentiated equation. If instead of the Laplace operator is differentiated Tricomi's operator, we obtain the mixed-composite type operator. For the equation of such a complicated nature, A. Birsadze formulated a great number of actual problems and obtained important results.

We have mentioned above the nonlocal problem in which the values of an unknown solution are interconnected at different boundary points. Of practical and theoretical interest are the problems, in which the boundary values of solutions are connected by the specific law with their values on a set of interior points of the domain. Among the problems of such a kind the Bitsadze-Samarski's problem takes central place. Its simplest and visual version is formulated as follows: Find in a unit circle a harmonic function u satisfying the condition

$$u(x,y) - u(\delta x, \delta y) = f(x,y), \ \ x^2 + y^2 = 1,$$

where the constant $\delta \in (0,1)$.

Practical problems in modeling are reduced, mainly, to the nonlinear equations. This is, seemingly, the fact that explains special interest to the above formulated problems. The powerful methods used for linear equations, in the nonlinear case are not always effective. It is a great advantage to reveal even a separate class of their solutions. The constructed by A. Bitsadze exact solutions of special type nonlinear equations

$$\sum_{i,j=1}^{n} a^{ij}(x) \Big[\frac{\partial^2 u}{\partial x_i \partial x_j} - b(u) \, \frac{\partial u}{\partial x_i} \, \frac{\partial u}{\partial x_j} \Big] + \sum_{i=1}^{n} c^i(x) \, \frac{\partial u}{\partial x_i} + d(x,u) = 0 \tag{4}$$

have found versatile practical and theoretical applications. Equations of type (4) cover a large number of models corresponding to the well-known equations of gravitation field, ferromagnetism theory, Heisenberg equations and Lorentz-covariant equations.

A large number of A. Bitsadze's creative achievements, including those mentioned above, have become long ago a corner stone on which scientific trends in the modern theory of partial differential equations are constructed.

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