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SOME COMMON FIXED POINT THEOREMS IN CONVEX METRIC SPACES

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ABSTRACT

In this paper we prove a generalization of Theorem 2 from [3] on the existence of the common fixed point for three mappings A, S and T in convex metric spaces. A theorem on continuous dependence of the common fixed points on parameter is obtained. As an application a generalization of the Krasnoselski fixed theorem is given.

1. PRELIMINARIES

First, we shall recall some definitions and results which we use in the paper.

A metric space (M,d) is *convex* if for each $x,y \in M$ such that $x \neq y$ there exists $z \in M$, $x \neq z \neq y$ such that:

$$d(x,z) + d(z,y) = d(x,y).$$

The following result is well known [1]:

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Proposition 1. *Let* K *be a closed subset of the complete and convex metric space* (M,d). *If* $x \in M$ *and* $y \notin M$ *then there exists a point* $z \in \partial K$ *such that:*

$$d(x,z) + d(z,y) = d(x,y).$$

Some fixed point theorems in convex metric spaces are proved in [1], [3], [4], [5], [6], [10], [11], [13], [14].

W. Takahashi introduced in [13] the notion of a convex structure W on a metric space (M,d).

Definition 1. *Let* (M,d) *be a metric space. A mapping* $W : M \times M \times [0,1] \to M$ *is called a convex structure on* M *if for all points* $(x,y) \in M \times M$ *and* $t \in [0,1]$:

$$d(u,W(x,y,t)) \le td(u,x) + (1-t)d(u,y)$$

for all $u \in M$.

In [14] it is proved that:

$$d(x,W(x,y,t)) = (1-t)d(x,y)$$

$$d(y,W(x,y,t)) = t\cdot d(x,y)$$

for every $x,y \in M$ and $t \in [0,1]$. From this it follows that a metric space with a convex structure is a convex metric space. Every normed space $(M,\|\|)$ is a metric space with a convex structure where $W(x,y,t) = t\cdot x + (1-t)y$, $(x,y,t) \in M \times M \times [0,1]$. An another example of a non normed metric space with a convex structure is given in [13].

Some fixed point theorems in metric spaces with a convex structure are proved in [3], [4], [10], [11], [13], [14].

In [14] L. Talman introduced a class of metric spaces with a convex structure for which a fixed point theorem of Schauder's type holds.

Definition 2. *Let* (M,d) *be a metric space and*

$P = \{(t_1,t_2,t_3) \in [0,1]^3,\ t_1 + t_2 + t_3 = 1\}$. *A strong convex structure (SCS) on* M *is a continuous function* $K : M \times M \times M \times P \to M$ *with the property that for each* $(x_1,x_2,x_3,t_1,t_2,t_3) \in M \times M \times M \times P$, $K(x_1,x_2,x_3,t_1,t_2,t_3)$ *is the unique point of* M *which satisfies:*

$$d(y,K(x_1,x_2,x_3,t_1,t_2,t_3)) \leq \sum_{k=1}^{3} t_k d(y,x_k)$$

for every $y \in M$.

A metric space (M,d) with a strong convex structure is called strongly convex. A strongly convex metric space is a metric space with the convex structure W_K, defined by:

$$W_K(x_1,x_2,t) = K(x_1,x_2,x_3,t,1-t,0)$$

$(x_1,x_2,t) \in M \times M \times [0,1]$.

If $H \subset M$ and (M,d) is a metric space with a convex structure W, H is said to be W convex if and only if $W(x,y,t) \in H$, for every $(x,y,t) \in H \times H \times [0,1]$.

If $S \subseteq M$, (M,d) is a metric space with a convex structure and $r > 0$ then $S_r = \{x \in M, d(x,S) < r\}$. A convex subset S of M is *stable* if the set S_r is convex for every $r > 0$.

Definition 3. *A strongly convex metric space* (M,d) *is stable if the set* $\{W(x,y,t),\ t \in [0,1]\}$ *is stable for every pair* $(x,y) \in M$.

In [14] it is proved that in a stable strongly convex metric space the convex hull of any precompact subset of M is precompact.

From Theorem 4.2 [14] we have the following result.

Proposition 2. *Let* (M,d) *be a complete, stable strongly convex metric space and* $F : M \to M$ *a compact mapping mapping. Then* F *has a fixed point.*

2. COMMON FIXED POINT THEOREMS

The following theorem is a generalization of Theorem 2 from [3] and of the well known result of Assad and Kirk [1] for the single-valued mapping.

Definition 4.[12] *Let* (M,d) *be a metric space,* K *a nonempty subset of* M *and* $f, S : K \to M$. *The pair* (f,S) *is weakly commutative if for every* $x \in K$ *the implication:*

$$fx, Sx \in K \Rightarrow d(fSx, Sfx) \leq d(fx, Sx)$$

*holds.**

There are examples of weakly commutative pairs (f,S) which are not commutative [7].

Theorem 1. *Let* (M,d) *be a complete, convex metric space,* K *a nonempty, closed subset of* M, $f,S,T : K \to M$ *continuous mappings so that* $\partial K \subseteq SK \cap TK$, $f(K) \cap K \subseteq SK \cap TK$ *and:*

$$Tx \in \partial K \Rightarrow fx \in K, \quad Sx \in \partial K \Rightarrow fx \in K.$$

If (f,S) *and* (f,T) *are weakly commutative and there exists a nondecreasing function* $q : [0,\infty) \to [0,1)$ *such that:*

$$d(fx,fy) \leq q(d(Sx,Ty))d(Sx,Ty)$$

then there exists $z \in K$ *so that:*

$$z = fz \in \{Tz, Sz\}.$$

If $S,T : M \to M$ *then there exists one and only one* $z \in K$ *such that* $z = fz = Tz = Sz$.

Proof. As in [3] it can be proved that there exist two sequences $\{p_n\}$ and $\{p'_n\}$ such that $p'_{n+1} = f(p_n)$, for every $n \in \mathbb{N}$ and:

**If* $S:M \to M$ *the implication is:* $Sx \in K \Rightarrow d(fSx,Sfx) \leq d(fx,Sx)$.

(i) For every $n \in \mathbb{N}$:

$$p'_{2n} \in K \Rightarrow p'_{2n} = Tp_{2n}$$
$$p'_{2n} \notin K \Rightarrow Tp_{2n} \in \partial K$$

and

$$d(Sp_{2n-1},Tp_{2n}) + d(Tp_{2n},fp_{2n-1}) = d(Sp_{2n-1},fp_{2n-1}).$$

(ii) For every $n \in \mathbb{N}$:

$$p'_{2n+1} \in K \Rightarrow p'_{2n+1} = Sp_{2n+1}$$
$$p'_{2n+1} \notin K \Rightarrow Sp_{2n+1} \in \partial K$$

and

$$d(Tp_{2n},Sp_{2n+1}) + d(Sp_{2n+1},fp_{2n}) = d(Tp_{2n},fp_{2n}).$$

For the completeness we shall give the proof of (i) and (ii). Let $x \in \partial K$. From $\partial K \subseteq T(K)$ it follows that there exists $p_0 \in K$ such that $x = Tp_0 \in \partial K$. Since $Tp_0 \in \partial K \Rightarrow fp_0 \in K$ we have that $fp_0 \in f(K) \cap K \subseteq S(K)$. Hence there exists $p_1 \in K$ so that $Sp_1 = fp_0 = p'_1$. Let $p'_2 = fp_1$. If $fp_1 \in K$ then $fp_1 \in f(K) \cap K \subseteq T(K)$ and so there exists $p_2 \in K$ such that $Tp_2 = fp_1$. If $fp_1 \notin K$ then there exists $q \in \partial K$ so that:

(1) $$d(Sp_1,q) + d(q,fp_1) = d(Sp_1,fp_1).$$

From $\partial K \subseteq T(K)$ it follows that there exists $p_2 \in K$ so that $q = Tp_2$ and hence (1) gives:

$$d(Sp_1,Tp_2) + d(Tp_2,fp_1) = d(Sp_1,fp_1).$$

If we continue in this way we can prove (i) and (ii).

Let:

$$P_0 = \{p_{2i} \mid i \in \mathbb{N}, p'_{2i} = Tp_{2i}\}$$
$$P_1 = \{p_{2i} \mid i \in \mathbb{N}, p'_{2i} \neq Tp_{2i}\},$$
$$Q_0 = \{p_{2i+1} \mid i \in \mathbb{N}, p'_{2i+1} = Sp_{2i+1}\}.$$

$$Q_1 = \{p_{2i+1} \mid i \in \mathbb{N}, p'_{2i+1} \neq Sp_{2i+1}\}.$$

Let us prove that for every $n \in \mathbb{N}$:

$$(p_{2n}, p_{2n+1}) \notin P_1 \times Q_1 \text{ and } (p_{2n-1}, p_{2n}) \notin Q_1 \times P_1.$$

Suppose that $p_{2n} \in P_1$ which means that $p'_{2n} \neq Tp_{2n}$. Then (i) implies that $Tp_{2n} \in \partial K$ and so $fp_{2n} \in K$. Then $p'_{2n+1} = Sp_{2n+1} = fp_{2n}$ and so $p_{2n+1} \in Q_0$. Similarly we can prove that

$$(p_{2n-1}, p_{2n}) \notin Q_1 \times P_1.$$

We shall prove that for every $n \geq 2$.

$$d(Tp_{2n}, Sp_{2n+1}) \leq \begin{cases} q(d(Sp_{2n-1}, Tp_{2n}))d(Sp_{2n-1}, Tp_{2n}) \\ \text{or} \\ q(d(Tp_{2n-2}, Sp_{2n-1}))d(Tp_{2n-2}, Sp_{2n-1}) \end{cases}$$

$$d(Sp_{2n-1}, Tp_{2n}) \leq \begin{cases} q(d(Tp_{2n-2}, Sp_{2n-1}))d(Tp_{2n-2}, Sp_{2n-1}) \\ \text{or} \\ q(d(Tp_{2n-2}, Sp_{2n-3}))d(Tp_{2n-2}, Sp_{2n-3}). \end{cases}$$

Let:

1. $(p_{2n}, p_{2n+1}) \in P_0 \times Q_0$.

Then:

$$d(Tp_{2n}, Sp_{2n+1}) = d(fp_{2n-1}, fp_{2n}) \leq$$

$$\leq q[d(Sp_{2n-1}, Tp_{2n})]d(Sp_{2n-1}, Tp_{2n}).$$

Let:

2. $(p_{2n}, p_{2n+1}) \in P_0 \times Q_1$.

We have that:

$$d(Tp_{2n},Sp_{2n+1}) \le d(Tp_{2n},fp_{2n}) = d(fp_{2n-1},fp_{2n})$$

$$\le q[d(Sp_{2n-1},Tp_{2n})]d(Sp_{2n-1},Tp_{2n}).$$

Let:

3. $(p_{2n},p_{2n+1}) \in P_1 \times Q_0$.

We have:

$$d(Tp_{2n},Sp_{2n+1}) \le d(Tp_{2n},fp_{2n-1}) + d(fp_{2n-1},fp_{2n})$$

since $p_{2n+1} \in Q_0$ and hence $Sp_{2n+1} = fp_{2n}$. Further:

$$d(Tp_{2n},Sp_{2n+1}) \le d(Tp_{2n},fp_{2n-1}) +$$

$$+ q[d(Sp_{2n-1},Tp_{2n})]d(Sp_{2n-1},Tp_{2n})$$

$$\le d(Sp_{2n-1},Tp_{2n}) + d(Tp_{2n},fp_{2n-1}) = d(Sp_{2n-1},fp_{2n-1}).$$

From $p_{2n} \in P_1$ it follows that $p_{2n-1} \in Q_0$ and so $Sp_{2n-1} = fp_{2n-2}$. This implies that:

$$d(Tp_{2n},Sp_{2n+1}) \le d(fp_{2n-2},fp_{2n-1}) \le$$

$$\le q[d(Tp_{2n-2},Sp_{2n-1})]d(Tp_{2n-2},Sp_{2n-1}).$$

We can prove in a similar way that the following implications hold:

$$(p_{2n-1},p_{2n}) \in Q_0 \times P_0 \Rightarrow d(Sp_{2n-1},Tp_{2n}) \le$$

$$\le q[d(Tp_{2n-2},Sp_{2n-1})]d(Tp_{2n-2},Sp_{2n-1})$$

$$(p_{2n-1},p_{2n}) \in Q_1 \times P_0 \Rightarrow d(Sp_{2n-1},Tp_{2n}) \le$$

$$\le q[d(Tp_{2n-2},Sp_{2n-3})]d(Tp_{2n-2},Sp_{2n-3})$$

$$(p_{2n-1},p_{2n}) \in Q_0 \times P_1 \Rightarrow d(Sp_{2n-1},Tp_{2n}) \le$$

$$\le q[d(Tp_{2n-2},Sp_{2n-1})]d(Tp_{2n-2},Sp_{2n-1}).$$

Let $\delta = max\{d(Tp_2,Sp_3),d(Tp_2,Sp_1)\}$. We shall prove that:

(2) $$d(Tp_{2n},Sp_{2n+1}) \le [q(\delta)]^{n-1}\delta$$

(3) $$d(Sp_{2n+1},Tp_{2n+2}) \le [q(\delta)]^{n}\delta$$

for every $n \in N$. For $n = 1$ we have that $d(Tp_2,Sp_3) \le \delta$ and:

$$d(Sp_3,Tp_4) \le q[d(Tp_2,Sp_3)]d(Tp_2,Sp_3) \le q(\delta)\delta$$

or:

$$d(Sp_3,Tp_4) \le q[d(Tp_2,Sp_1)]d(Tp_2,Sp_1) \le q(\delta)\delta.$$

Suppose that (2) and (3) are satisfied for $n = k$ and prove that:

(4) $$d(Tp_{2k+2},Sp_{2k+3}) \le [q(\delta)]^{k}\delta$$

(5) $$d(Tp_{2k+4},Sp_{2k+3}) \le [q(\delta)]^{k+1}\delta$$

We have that:

$$d(Tp_{2k+2},Sp_{2k+3}) \le q[d(Sp_{2k+1},Tp_{2k+2})]d(Sp_{2k+1},Tp_{2k+2})$$

$$\le q[(q(\delta))^{k}\delta][q(\delta)]^{k}\delta \le [q(\delta)]^{k+1}\cdot\delta$$

or:

$$d(Tp_{2k+2},Sp_{2k+3}) \le q[(Tp_{2k},Sp_{2k+1})]d(Tp_{2k},Sp_{2k+1})$$

$$\le q[(q(\delta))^{k-1}\delta][q(\delta)]^{k-1}\delta \le [q(\delta)]^{k}\delta,$$

which proves (4). Inequality (5) can be proved similarly. Hence (2) and (3) are satisfied for every $n \in N$. From (2) and (3) it is obvious that $\{Tp_{2n}\}$ and $\{Sp_{2n+1}\}$ are Cauchy sequences in K. Since M is complete we obtain that there exists $z \in K$ so that $z = \lim_{n\to\infty} Tp_{2n} = \lim_{n\to\infty} Sp_{2n+1}$. There exists at least one subsequence $\{Tp_{2n_k}\}$ or $\{Sp_{2n_k+1}\}$ such that for every $k \in N$, $p_{2n_k} \in P_0$ or $p_{2n_k+1} \in Q_0$. We shall suppose that $p_{2n_k} \in P_0$ $(k \in N)$. Then $fp_{2n_k-1} \in K$ and $Tp_{2n_k} = fp_{2n_k-1}$ for every $k \in N$.

The pair (f,S) is weakly commutative which implies that $Sz = fz$, which can be easily proved [3].

Further for every $k \in N$:

$$(6) \qquad d(fp_{2n_k}, fSp_{2n_k-1}) \le q[d(Tp_{2n_k}, S(Sp_{2n_k-1}))] \cdot \cdot d(Tp_{2n_k}, S(Sp_{2n_k-1}))$$

and

$$(7) \qquad d(fp_{2n_k}, fp_{2n_k-1}) \le q[d(Tp_{2n_k}, Sp_{2n_k-1})] \cdot d(Tp_{2n_k}, Sp_{2n_k-1}) \le d(Tp_{2n_k}, Sp_{2n_k-1}).$$

Since $\lim_{k\to\infty} Tp_{2n_k} = \lim_{k\to\infty} fp_{2n_k-1} = z$ from (7) we obtain that $z = \lim_{k\to\infty} fp_{2n_k-1} = \lim_{k\to\infty} fp_{2n_k}$. On the other side $d(Tp_{2n_k}, S(Sp_{2n_k-1})) \le M$ $(k \in N)$ since $\lim_{k\to\infty} d(Tp_{2n_k}, S(Sp_{2n_k-1})) = d(z,Sz)$. Hence (6) implies that:

$$(8) \qquad d(fp_{2n_k}, fSp_{2n_k-1}) \le q(M) d(Tp_{2n_k}, S(Sp_{2n_k-1}))$$

and since $\lim_{k\to\infty} fSp_{2n_k-1} = \lim_{k\to\infty} Sfp_{2n_k-1}$ we obtain from (6) that:

$$d(z,Sz) \le q(M) d(z,Sz).$$

Suppose that $T : M \to M$ and prove that $Tz = fz$. Then from:

$$d(fp_{2n_k}, fp_{2n_k-1}) = d(fp_{2n_k}, Tp_{2n_k}) \le$$

$$\le q[d(Tp_{2n_k}, Sp_{2n_k-1})] d(Tp_{2n_k}, Sp_{2n_k-1}) \le$$

$$\leq d(Tp_{2n_k}, Sp_{2n_k-1})$$

it follows that $\lim_{k\to\infty} fp_{2n_k} = z$ and so:

$$Tz = \lim_{k\to\infty} T(fp_{2n_k}) = \lim_{k\to\infty} f(Tp_{2n_k}) = fz.$$

The following theorem is a theorem on continuous dependence of the common fixed points on the parameter.

Theorem 2. *Let* (M,d) *be a complete, convex metric space,* K *a nonempty closed subset of* M, U *a topological space,* $f : K \times U \to M$ *such that for every* $u \in U$, $f(\cdot,u)$ *is continuous on* K *and for every* $x \in K$ $f(x,\cdot)$ *is continuous on* U, S *and* T *continuous mappings from* M *into* M *so that* $\partial K \subseteq SK \cap TK$, $f(K,U) \cap K \subseteq SK \cap TK$ *and for every* $u \in U$:

$$Tx \in \partial K \Rightarrow f(x,u) \in K, \quad Sx \in \partial K \Rightarrow f(x,u) \in K$$

where $x \in K$.

If there exists a nondecreasing function $q : [0,\infty) \to [0,1)$ *such that for every* $(x,y,u) \in K \times K \times U$:

$$d(f(x,u),f(y,u)) \leq q(d(Sx,Ty))d(Sx,Ty),$$

the set $f(K,U) \cap K$ *is bounded and for every* $u \in U$ *the pairs* $(f(\cdot,u),S)$ *and* $(f(\cdot,u),T)$ *are weakly commutative then there exists the unique continuous mapping* $z : u \mapsto z(u)$ $(u \in U)$, *from* U *into* K *such that:*

$$z(u) = f(z(u),u) = Sz(u) = Tz(u), \ u \in U.$$

Proof. It is obvious that for every $u \in U$ there exists one and only one element $z(u) \in K$ such that $z(u) = f(z(u),u) = Sz(u) = Tz(u)$. We shall prove that the mapping $u \mapsto z(u)$ is continuous at every point $u_0 \in U$. Let $\varepsilon > 0$. We have to prove that there exists a neighbourhood $V(u_0) \subseteq U$ of u_0 so that the following implication holds:

(9) $u \in V(u_0) \Rightarrow d(z(u),z(u_0)) < \varepsilon.$

Since $z(u) \in f(K,U) \cap K$ and the set $f(K,U) \cap K$ is bounded, there exists $P > 0$ such that:

$$d(z(u),z(u_0)) \leq P, \quad \text{for every } u \in U.$$

Then we have:

$$\begin{aligned} d(z(u),z(u_0)) &\leq d(z(u),f(z(u_0),u)) + \\ &\quad + d(f(z(u_0),u),z(u_0)) \\ &= d(f(z(u),u),f(z(u_0),u)) + d(f(z(u_0),u),z(u_0)) \leq \\ &\leq q[d(Sz(u),Tz(u_0))]d(Sz(u),Tz(u_0)) + \\ &\quad + d(f(z(u_0),u),z(u_0)) = \\ &= q[d(z(u),z(u_0))]\cdot d(z(u),z(u_0)) + \\ &\quad + d(f(z(u_0),u),z(u_0)) \leq \\ &\leq q(P)d(z(u),z(u_0)) + d(f(z(u_0),u),f(z(u_0),u_0)). \end{aligned}$$

This implies that:

$$d(z(u),z(u_0)) \leq \frac{d(f(z(u_0),u),f(z(u_0),u_0))}{1 - q(P)}$$

and since for every $z \in K$, the mapping $u \mapsto f(z,u)$ is continuous it is obvious that thera exists $V(u_0)$ so that (9) holds.

Using Theorem 2 we shall prove a generalization of the Krasnoselski fixed point theorem and the Melvin fixed point theorem in convex metric spaces.

Theorem 3. *Let* (M,d) *be a complete strongly convex* *metric space whose SCS is stable,* K *a nonempty, closed convex subset of* M,Q : K → M *a compact mapping,* G : K × $\overline{Q(K)}$ → M, S,T : M → M *so that all the conditions of Theorem 2 are satisfied for* U = $\overline{Q(K)}$ *and* f(x,u) = G(x,u) (x ∈ K,u ∈ $\overline{Q(K)}$). *Then there exists at least one element* x ∈ K *such that* x = G(x,Q(x)) = Sx = Tx.

Proof. From Theorem 2 it follows that there exists one and only one continuous mapping R : $\overline{Q(K)}$ → K so that:

$$Ru = G(Ru,u) = SRu = TRu.$$

Define the mapping $\tilde{R}$: K → K in the following way: $\tilde{R}x$ = RQx for every x ∈ K. Then $\tilde{R}$ is a compact mapping and from Proposition 2 it follows that there exists x ∈ K such that $\tilde{R}x = x = RQx = G(RQx,Qx) = G(x,Qx) = Sx = Tx$.

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REZIME

NEKE TEOREME O NEPOKRETNOJ TAČKI U KONVEKSNIM METRIČKIM PROSTORIMA

U ovom radu se dokazuje jedno uopštenje teoreme 2 iz [3] o postojanju zajedničke nepokretne tačke za tri preslikavanja. Dobijena je teorema o neprekidnoj zavisnosti zajedničkih nepokretnih tačaka od parametra. Kao primena dato je jedno uopštenje teoreme Krasnoseljskog.

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